A Smart Application for Pocket Friendly and Composable Unit Manufacturing Models

Team Members:
Andrea Aguilera*, Abdulaziz Alrashed, Abdulazeez Alqahtani, Arun Bala Subramaniyan and Rong Pan*

Arizona State University

* Participants with US citizenship:
Andrea Aguilera, email: aaguile6@asu.edu

Primary Contact: Rong Pan, email: Rong.Pan@asu.edu (480-335-2935)

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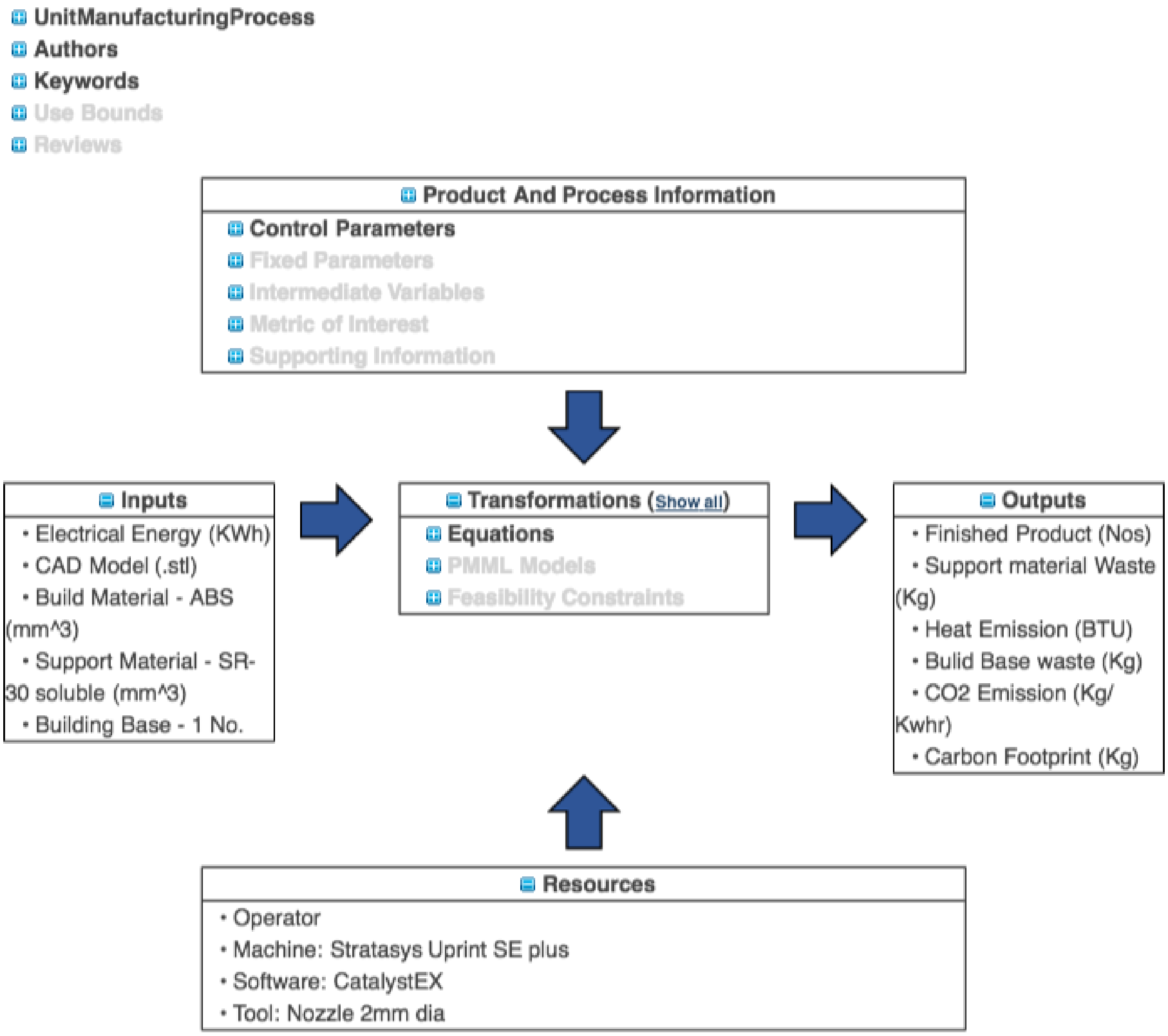
The objective of this project is to build a user-friendly application to aid in various manufacturing tasks like making the process plan, tracking the material flow, decision making using environmental and economic tradeoff analysis with various sustainability metrics, reduce waste (lean manufacturing). The objectives are fulfilled by building a set of UMP models as per ASTM E60.13 E3012-16 standard [1] using the UMP builder from NIST [2]. The manufacturing processes considered in our study are Milling, Drilling and Fused Deposition Modeling. A brief introduction of the processes is given below followed by their respective UMP models.

Fused Deposition Modeling (Non-Traditional Manufacturing Process):

The Fused Deposition Modeling (3-D printing) is a non-traditional manufacturing process that makes 3-dimensional solid objects and shapes. This process is the opposite of the traditional machining processes (subtractive processes) and has more advantages than the traditional processes. A 3-D printer can model and create complicated shapes of materials with less workflow, which is the most important feature of this process. Modern day 3-D printers can optimize geometries, create lightweight and complicated components with reduced material and energy consumption.

UMP model for FDM (excluding washing) process:



Product And Process Information

Control Parameters

- Initial Area of Building Base (mm^2)
- Area of ith Polygon
- Number of layers
- Fraction of Area of build material filled actually by build material
- build Time for Part material for layer i (sec)
- Fraction of Area of support material filled actually by support material
- Build Time for Support Material for layer i (sec)
- Build time for layer i (sec)
- Time to move table in z-direction (sec)
- Total Build Time (hrs)
- Total time for part material building (sec)
- Total Time for support material building (hrs)
- Volume of building material used (mm^3)
- Area of building Base (mm^2)
- Volume of support material used (mm^3)
- Cost of material used ($)
- Total operation time (hrs)
- Energy Usage (KWhr)
- Energy Cost ($)
- Total Heat Expelled (BTU)
- Tip Life remaining (hrs)
- Tipe-wipe assembly Life remaining (hrs)
- Volume of Material Remaining (mm^3)
- Percentage of Material remaining (%)
- Area of Building Base used (mm^2)
- Area of Building Base remaining (mm^2)
- Carbon Emission (Kg)
- Surface Roughness
- Mass of material
- Process Productivity
- Specific Energy Consumption (KWhr/Kg)
- Carboon Footprint Production (Kg)
- Carboon Footprint Recycling (Kg)
- Cost of Product ($)
- Number of product that can be manufactured (Nos)
- Number of baseplates required (Nos)
- Horizontal Swell ratio

Fixed Parameters

Intermediate Variables

Metric of Interest

Supporting Information


Inputs
Electrical Energy (KWh)
CAD Model (.stl)
Build Material - ABS (mm^3)
Support Material - SR-30 soluble (mm^3)
Building Base - 1 No.
Transformations (Show all)
Equations
Initial Area of Building Base
Number of Layers
Fraction of Area building
build Time for Part building
Fraction of Area support
Build Time for Support
Build time for layer i (sec)
Time to move table
Total Build Time (hrs)
Total time for part building
Total Time for support
Volume of building used
Volume of support used
Cost of material used ($)
Total operation time (hrs)
Energy Usage (KWhr)
Energy Cost ($)
Total Heat Expelled
Tip Life remaining (hrs)
Tipe-wipe assembly Life remain
Volume of building Remain
Volume of Support Remain
Percentage of building remain
Percentage of Support remain
Area of Building Base used
Area of Building Base remain
Carbon Emission (Kg)
Surface Roughness
Surface Roughness
Horizontal Swell ratio
Surface Roughness
Mass of building
Mass of support
Process Productivity
Specific Energy Consumption
Carboon Footprint Production
Carboon Footprint Production
Carboon Footprint Recycling
Carboon Footprint Recycling
Cost of Product ($)
Number of product (Nos)
Area of ith Polygon
Number of baseplates required
PMML Models
Feasibility Constraints
Outputs
Finished Product (Nos)
Support material Waste (Kg)
Heat Emission (BTU)
Bulid Base waste (Kg)
CO2 Emission (Kg/ Kwhr)
Carbon Footprint (Kg)
Resources
Operator
Machine: Stratasys Uprint SE plus
Software: CatalystEX
Tool: Nozzle 2mm dia

Full list of transformations

Initial Area of Building Base: $A_{BB_{ini}} = BB_L \times BB_W$

Number of Layers: $N = int(H/z_t)$

Fraction of Area building: $d_b = RW_b/(RW_b + Fill_{AG})$

build Time for Part building: $T_{b_i} = d_b \times \left(ACS_{Poly_i}/\left(RW_b \times HV\right)\right)$

Fraction of Area support: $d_s = RW_s/(RW_s + AG_s)$

Build Time for Support: $T_{s_i} = d_s \times \left(ACS_{sup_{poly_i}}\right)/\left(RW_s \times HV\right)$

Build time for layer i (sec): $T_i = T_{bi} + T_{si}$

Time to move table: $T_{zmove} = z_t/TV_z$

Total Build Time (hrs): $T = \left(sum\left(T_i\right) + \left(N \times T_{zmove}\right) + \left(\left(N/m\right) \times T_{wipe}\right)\right)/3600$

Total time for part building: $T_b = \left(sum\left(T_{b_i}\right)/3600\right)$

Total Time for support: $T_s = \left(sum\left(T_{si}\right)/3600\right)$

Volume of building used: $V_b = sum\left(ACS_{Poly}\right) \times z_t$

Volume of support used: $V_s = sum\left(ACS_{sup_{poly}}\right) \times z_t + \left(Base \times 15 \times z_t\right)$

Cost of material used (\$): $C_{mat} = (V_b + C\cos t_b) + (V_s \times Cost_s)$

Total operation time (hrs): $T_o = T + \left(T_{warmup}/60\right) + \left(T_{cooldown}/60\right)$

Energy Usage (KWhr): $E = T_o \times PR$

Energy Cost (\$): $C_e = E \times C_{perKW}$

Total Heat Expelled: $T_{heat} = T_o \times H_{per_{hr}}$

Tip Life remaining (hrs): $T_{tip} = TL_{initial} - \left(T_b + T_s\right)$

Tipe-wipe assembly Life remain: $T_{tip_{wipe}} = TW_{initial} - \left(T - \left(\left(sum\left(T_i\right) + \left(N \times T_{zmove}\right)\right)/3600\right)\right)$

Volume of building Remain: $VR_b = Vol_{b_{initial}} - V_b$

Volume of Support Remain: $VR_s = Vol_{s_{initial}} - V_s$

Percentage of building remain: $PVR_b = 1 - \left(V_b/Vol_{b_{initial}}\right)$

Percentage of Support remain: $PVR_s = 1 - \left(V_s/Vol_{s_{initial}}\right)$

Area of Building Base used: $BB_{used} = 1.05 \times max\left(ACS_{poly}\right)$

Area of Building Base remain: $A_{BB_{rem}} = A_{BB_{ini}} - BB_{used}$

Carbon Emission (Kg): $CO_{2_{emission}} = E \times CO_{2_{EF}}$

Surface Roughness: $For\ (\theta \geq 0\ and\ \theta \leq 70):$

$$SR = 70 \times (z_t/(\cos(\theta)))$$

Surface Roughness: $For\ (\theta = 90):$

$$SR = 112.5 \times z_t$$

Horizontal Swell ratio: $HSR = RW_b/D$

Surface Roughness: $For\ (\theta > 70\ and\ \theta < 90):$

$$SR = 0.05 \times ((90 \times SR_{70}(70)) - (70 \times SR_{90}(90)) + \theta \times (SR_{90}(90) - SR_{70}(70))$$

Mass of building: $m_b = Den_b \times V_b$

Mass of support: $m_s = Den_s \times V_s$

Process Productivity: $PP = (m_b + m_s)/(T_b + T_s)$

Specific Energy Consumption: $SEC = (PR/PP)$

Carboon Footprint Production: $CO_{2F_b} = m_b \times CO_{2FF_b}$

Carboon Footprint Production: $CO_{2F_s} = m_s \times CO_{2FF_s}$

Carboon Footprint Recycling: $CO_{2FR_b} = m_b \times CO_{2FFR_b}$

Carboon Footprint Recycling: $CO_{2FR_s} = m_s \times CO_{2FFR_s}$

Cost of Product (\$): $C_p = C_{mat} + C_e + Cost_{misc}$

Number of product (Nos): $NP = min\left(floor\left(\left(Vol_{b_{initial}}/V_b\right), \left(Vol_{s_{initial}}/V_s\right)\right)\right)$

Area of ith Polygon: $A_i = \frac{1}{2}\left|\left(\sum_{j=1}^{n-1} x_j y_{j+1} + x_n y_1\right) - \left(\sum_{j=1}^{n-1} x_{j+1} y_j + x_1 y_n\right)\right|$

Number of baseplates required: $N_{BB} = ceil\left(NP/\left(A_{BB_{ini}}/BB_{used}\right)\right)$

Drilling (Traditional Manufacturing Process)

Drilling is a material removal process that uses a drill bit (rotary cutting edge tool) to cut a hole through a solid metal, usually in a circular cross-section. The bit rotates at hundreds and even thousands of rates per minute, and it is pressed against the workpiece, whose metal is softer than the drill bit, and cuts chips off the workpiece. There are different types of drilling, such as: spot drilling (drilling a hole that guides for drilling the final hole), center drilling (to drill countersink center holes in a workpiece to be mounted between centers for grinding or turning), deep hole drilling, micro drilling (drilling holes smaller than 0.5mm), etc.

UMP model for Drilling process:

UnitManufacturingProcess

- **id** *5ab18da322dab7002e64daac*
- **name** *Drilling*
- **timestamp** *2018-03-20*
- **reviewed** *false*
- **typeOfProcess** *Traditional*
- **description**

Material Removal Process

Authors

- **Name:** *Andrea Aguilera* **Organization:** *ASU*

Keywords

- *Total time, power consumption*

Use Bounds

Reviews

Product And Process Information

Control Parameters

- Feed rate
- Pbasic
- Tidle
- Tdrilling
- d
- f
- N
- VRR
- specific cutting energy
- Thandling
- AirTime
- approach
- Pdrilling
- over travel times
- retraction times
- LoadingTime
- cleaningTime
- unloadingTime
- loadUnloadTime
- Total Time
- Pcoolant
- Pspindle
- Paxis
- Tbasic
- Pidle

Fixed Parameters

- Pbasic

Intermediate Variables

Metric of Interest

Supporting Information

Inputs

- Raw Material

Transformations (Show all)

Equations

- Etotal
- Ptotal
- Eprocess
- Tbasic
- Ebasic
- LoadUnloadTime
- Pidle
- Eidle
- Thandling
- IdleTime
- E
- Edrilling
- Pdrilling
- Tdriling

PMML Models

Feasibility Constraints

Outputs

- Finished part

Resources

- work station
- Drilling machine

Full list of transformations

Etotal: $Etotal = Pbasic * (Tbasic) + Pidle * (Tidle) + Pdrilling * (Tdrilling)$

Ptotal: $Ptotal = (Eprocess)/(Ttotal)$

Eprocess: $Eprocess = Edrilling + Eidle + Ebasic$

Tbasic: $Tbasic = LoadUnloadTime + Tidle$

Ebasic: $Ebasic = Pbasic * Tbasic$

LoadUnloadTime: $LoadUnloadTime = loadingTime + cleaningTime + unloadingTime$

Pidle: $Pidle = Pspindle + Pcoolant + Paxis$

Eidle: $Eidle = Tidle * Pidle$

Thandling: $Thandling = AirTime + (approach/overtraveltimes) + retractiontimes$

IdleTime: $IdleTime = Thandling + Tdrilling$

E: $E = Tdrilling * VRR * specificcuttingenergy$

Edrilling: $Edrilling = Pdrilling * Tdrilling$

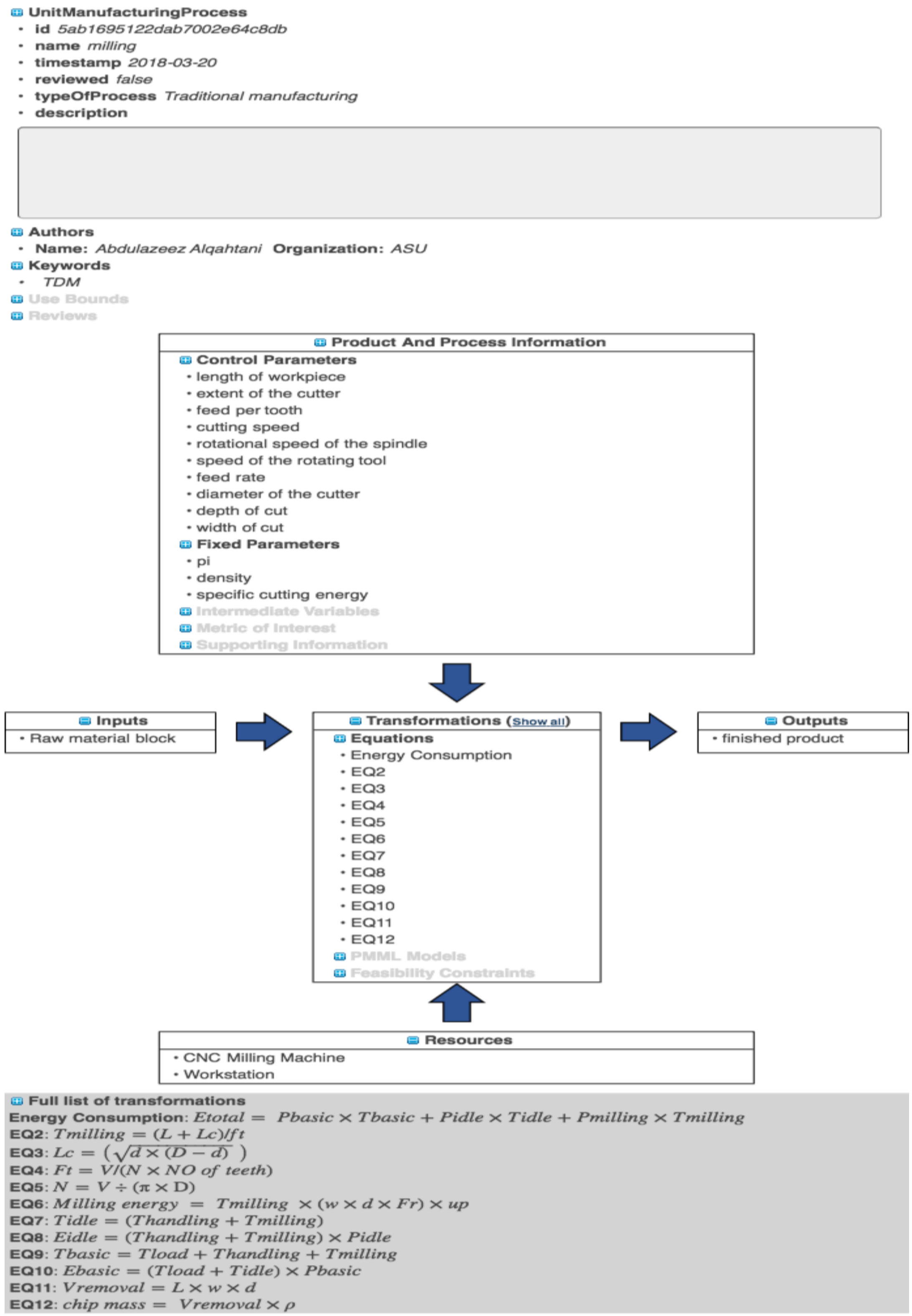
Pdrilling: $Pdrilling = VRR * specificcuttingenergy$

Tdriling: $Tdrilling = (d)/f * N$

Milling (Traditional Process)

Milling is also one of the traditional manufacturing processes. It helps to remove material from a workpiece by using a milling cutter (rotating cutting tool), which is attached to a spindle or arbor. A workpiece is a piece of material being worked on to remove unwanted material from it. Milling is basically used to produce parts that are not axially symmetric. In addition, it can be used to add or refine features on some parts that were manufactured using different processes.

UMP model for Milling process:



Description:

In today's manufacturing world, the phrases "Smart Manufacturing", "Manufacturing Automation" are becoming more and more trending due to the compelling motivation to reduce the manufacturing costs along with minimized environmental impacts. Hence, most of the manufacturers (both small scale and large scale industries) are exploring a variety of techniques to achieve the bottom line and compete in the current market. Research is being carried out on all forefronts to improve job scheduling, reduce lead time, cost analysis, uncertainty quantification, life cycle assessment, etc. One of the ways to reduce/alleviate the costs and to foresee the product going through each stage of manufacturing is through simulation in the virtual environment using the available physics based or data driven models. Though various research has been conducted over the decades, there is not a common place where the complete process models for each manufacturing processes are available. In addition, it is very common to have more than one process to manufacture a part. In our work, we attempt to develop a set of UMP models and automatically select the process(s) required for manufacturing the product based on the product design. The process models are then used to create a simple user friendly application capable of handling variety of metrics like time taken, energy consumption, material consumption etc. The UMP models are built based on the ASTM standards to support the NIST's goal of developing a unified framework for manufacturing processes. A good review of research directions for open UMP repository is provided by Bernstein et al [3]. The majority of the equations in our UMP models are obtained from references [4, 5]. The model for the FDM process was validated using the NIST additive manufacturing test artifact as shown in Figures 1 and 2.

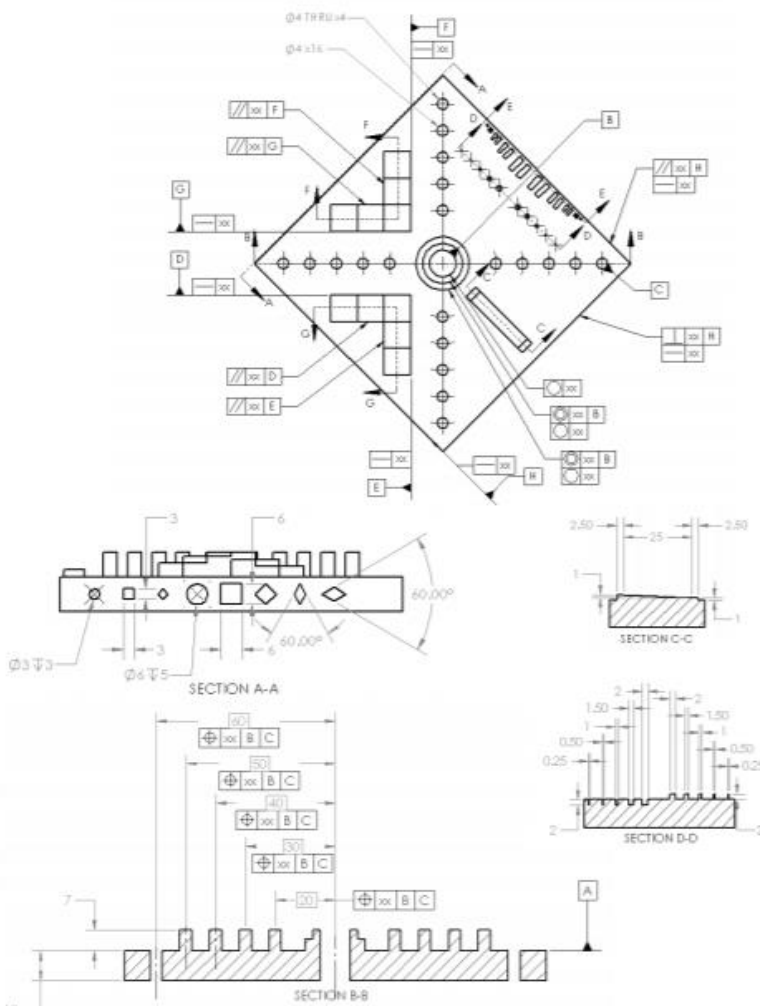


Fig. 1: NIST test artifact from Moylen et al [6]

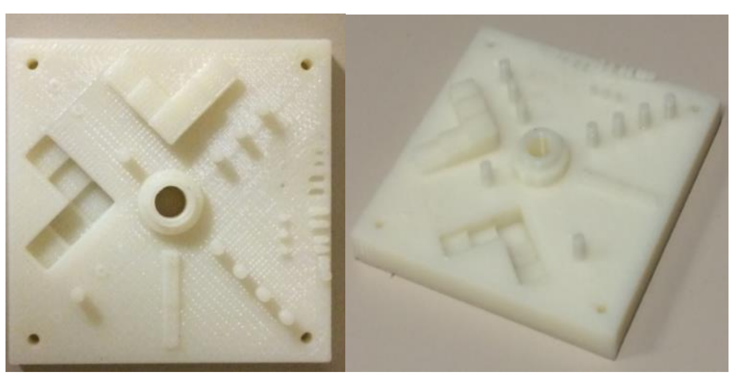


Fig. 2: 3D printed NIST's test artifact

The ABS plastic part was created using Stratasys Uprint SE plus with the deviation in the total time to build is around 16%. The Carbon Fiber composite part was created using Markforged Mark Two 3d printer but the deviation is high since it involves many additional parameters like fiber orientation, matrix sparsity, etc. The FDM model is being calibrated to handle both the plastic parts and fiber reinforced composites and will be updated further. The other two UMP models are yet to be validated using Intelitek BenchMill 6100 CNC machining center since the machines are still in the process of installation in our lab. The developed UMP models can be utilized in a variety of ways and we provide two practical use cases.

Case I:

Create user friendly application to aid manufacturing in virtual environment:

Since the UMP models will be uploaded in the NIST repository in (.XML) format, it is easy to read the xml content through the use of Application Programming Interface (API's) (Ex: weather data API from NOAA) and other sources. With that in mind, our team has created an app (http://127.0.0.1:6263) to simulate the FDM process that can be used to track the material flow, energy consumption, time taken, cost estimation in the production of I-Beam.

Right now, this app is hosted on dynamic IP and being shifted to static IP address. We are planning to have our own server for the manufacturing laboratory for further developments. In addition, we are also working on uploading to Github. The app is still in the initial phase and Fig. 3 shows the I-beam production simulation using FDM which allows the user to change the inputs on the slider on the left hand side and observe the output on the right hand side. In addition, the user can animate the entire process inputs (by clicking the play button) and observe the change in outputs like material remaining, number of layers printed, energy consumption, carbon footprint, total cost, and many more.

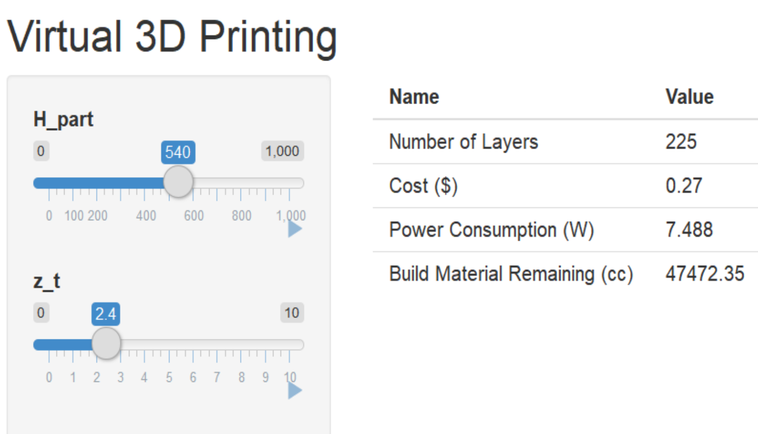


Fig 3: Screenshot of the developed application for Virtual 3d printing (FDM process)

Use case II:

Performance functions for Optimization problems:

Many optimization problems in manufacturing revolves around minimizing cost, energy, carbon emission, etc. But, in most cases, it is not possible to have a complete list of performance functions and the use of meta-models are common. In such cases, the complete list of process models from UMP repository will aid in achieving a better optimum solution since the performance functions can be called from the repository. Also, it will be helpful in verifying the accuracy of the developed meta models. In our case, we devised a simple optimization problem to choose between a traditional and non-traditional process to manufacture a batch of I-beams (n=10000) with two holes drilled on its top and bottom for clamping purpose.

Objective function: To minimize the cost of I-Beam production

Min n[y1(c3d * a + cmisc_t) + (1-y1)(cmisc_nt +cmill * b + cdrill * c)]

Constraints:

{y1 * power_3d * a} + (1-y1) {[b*power_mill + c*power_drill]} <= X watts

{y1 * carbon_3d * a} + (1-y1) {[b*carbon_mill + c*carbon_drill]} <= Y units

y1, a, b, c are binary and non-negative

Terms in objective function:

n = number of identical parts to be manufactured (ex: n = 10000)
y1 = binary variable (either 1 or 0)
c3d = cost of 3d printing from FDM UMP model
cmisc = miscellaneous cost of traditional/non-traditional process like operator cost and others
cmill = cost of milling obtained from milling UMP model
cdrill = cost of drilling from drilling UMP model

a, b, c are binary variables (either 1 or 0)

+++

Terms in constraint function:

power_3d = power consumption in 3d printing.
power_mill = power consumption in milling.
power_drill = power consumption in 3d drilling.

carbon_3d = carbon emission in 3d printing.
carbon_mill = carbon emission in milling.
carbon_drill = carbon emission in 3d drilling.

Note that this problem can still be solved without adding the binary variables (a,b,c) but in general, if there are large number of processes, and the same part can be produced by different combination of processes within each category of traditional or non-traditional processes, then these binary variables will be helpful in choosing the optimum combination of processes. Hence, they are included in our model. The above problem is solved using AMPL and the best process is to mill the raw material and drill the holes since the manufacturing cost of FDM is too high. But, for the batch production of complex shapes, it is possible to bring down the cost of FDM which will be investigated in future.

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