MIT 2.008 Design and Manufacturing II

Quiz 2 - Part A, In-Class Component

Spring 2024
May 8th, 2024

- You will have 80 minutes to complete this portion of the exam
- Closed Book, except that you are allowed one double-sided, hand written 8.5” x 11” notes sheet
- All work for CREDIT must be completed in this quiz document
- Calculators are allowed, and we have provided them in the room. Please return them at the end of the exam.

General Notes

- *For qualitative answers, we’re not looking for long essays. Please answer using short (1-2 sentence per answer) bullet points.*
- *For quantitative answers, show your work as clearly as possible. When possible, keep answers in algebraic form until plugging in numbers at the very end; this way, it is much easier for graders to understand where you make mistakes and provide meaningful feedback* ***(and partial credit)****.*

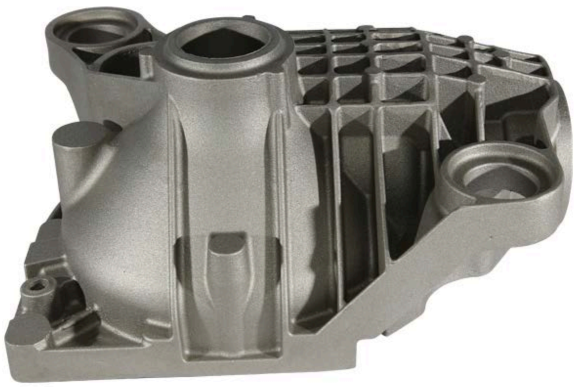
Name: ____________________________

Part A, In-Class Component		
Problem 1		Out of 15 points
Problem 2		Out of 31 points
Problem 3		Out of 24 points
Part B, Take-Home Component		
Problem 4		Out of 30 points
Total		**100 points**

<u>Problem 1 - Short Answers (15 points) (15 minutes)</u>

a) For each of the parts below, indicate the *<u>primary</u>* process used to manufacture the item (do not worry about secondary operations). Provide a brief rationale to justify your choice. **(5 minutes)**

6 pts total (0.5 point per correct choice, 1 point per rationale)

	*Primary manufacturing process* ***(circle one)*** Sand casting Investment (lost wax) casting Die casting Sheet metal bending
	Brief Rationale The geometry looks complex and not bent out of a 2D material. The surface finish is smooth which suggests slurry coating was used pointing to investment casting. Note: you could interpret the surface finish as not smooth, pointing to sand casting. Either answer is accepted so long as it is justified correctly.

	*Primary manufacturing process* ***(circle one)*** Sand casting Investment (lost wax) casting Die casting Sheet metal bending
	Brief Rationale The geometry looks complex and not bent out of a 2D material. Investment casting is preferable because a die cast will require multiple side pulls and a sand cast will not provide the appropriate surface finish.

<table>
<tr><td rowspan="2"></td><td>Primary manufacturing process (circle one)

Sand casting
Investment (lost wax) casting
Die casting
Sheet metal bending</td></tr>
<tr><td>Brief Rationale

The geometry looks complex and not bent out of a 2D material. The surface has ejector pin marks which suggest die casting.</td></tr>
</table>

<table>
<tr><td rowspan="2"></td><td>Primary manufacturing process (circle one)

Sand casting
Investment (lost wax) casting
Die casting
Sheet metal bending</td></tr>
<tr><td>Brief Rationale

The geometry looks like it is bent from 2D sheet metal. The part has uniform thickness, and one can see multiple bend radius which is a result of the bending process.</td></tr>
</table>

b) For the following prompts, indicate the correct choice and provide a brief rationale. **(10 minutes)**
9 pts total: 0.5 point per correct choice, 1 point per rationale

i) A contract manufacturer which primarily engages clients to make parts in prototype quantities is best organized in a (**job shop/transfer line/work cell**) structure.

Brief Rationale

Prototype parts are best made in a job shop environment because low volume parts are best suited for a job shop where there custom fixturing techniques and machining/processes can be achieved without investing into high fixed cost items (like molds). Since low quantity parts are needed, initial investment on tooling should be low to get a return on investment.

ii) A company will generally consider the rent or mortgage payment on its facility as a (**fixed/variable**) cost of production.

Brief Rationale

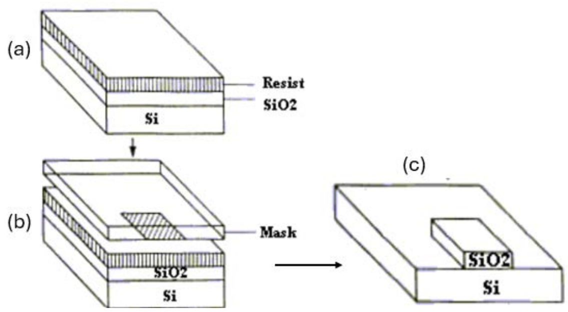
Mortgage payment is a fixed cost of production as it doesnt change with the number of parts produced (given the same area is used to produce more parts)

iii) A (**chemical vapor deposition/physical vapor deposition**) process is used to add a thin film layer via polymerization to a substrate using a gas as the source material.

Brief Rationale

Thin films can be deposited using a technique called Chemical Vapor Deposition (CVD). This process involves introducing a gas or vapor into a vacuum chamber containing a substrate. Through a thermal or plasma-assisted process, the gas or vapor reacts with the substrate to form a solid thin film

iv) Based on the mask in step b in the image below, the features produced on the substrate on the right were made with a (**positive/negative**) photoresist



Brief Rationale

The resulting SiO2 layer remaining is an extruded boss. Since the mask serves to protect this region from the subsequent subtraction/dissolving of the resist caused by UV light, it is considered to be a positive photoresist.

v) Aerospace companies are opting to replace metal components with polymer matrix composites for a variety of reasons. One way in which using components from metal is still preferable is (**weight/part strength/stiffness/cycle time**).

Brief Rationale

Polymer matrix composites need a significant amount of time (from ply cutting to layup to curing in autoclave. The manufacturing process is quite complex and needs to be done in a quality controlled area (to prevent entry of debris in the composite layers). All of such manufacturing complexity increases cycle time relative to machining. But the upside of composites is that strength/stiffness to weight ratio is quite high.

vi) When making an additively manufactured part, if print time and cost are primary considerations, that favors (**extrusion/photopolymerization**) as the printer choice.

Brief Rationale

Extrusion (FDM) is usually faster as the nozzle diameter, which usually dominates the layer thickness, is larger than the diameter of the light source that is used in photopolymerization. FDM is also cheaper as the machines have relatively inexpensive heater/extruder nozzle and cheap plastic printing material as opposed to more complicated parts like lens, UV source and expensive resins that are present in photopolymerization 3D printing machines.

Problem 2 - Forming (31 points) **(45 minutes)**

Below is a photo of a mounting bracket, primarily sold for as a mount for large motors.

For the questions below, we will ignore the cut holes and focus on the bracket itself, which is made with sheet metal bending. The panel is 4mm thick, and during bending operations, the initial radius of curvature is 10mm.

a) First, let us determine the degree of springback during a bending operation. Assuming that the bracket is made from aluminum (Young's Modulus 70 GPa, yield strength 40 MPa), calculate the radius of curvature after a single operation. **(5 minutes)**
4 pts total: 2 correct use of springback equation, 1 for correct Y/E/t, 1 final answer

$$\frac{R_i}{R_f} = 4\left(\frac{R_i}{t} \times \frac{Y}{E}\right)^3 - 3\left(\frac{R_i}{t} \times \frac{Y}{E}\right) + 1$$

$$R_f = \frac{R_i}{4\left(\frac{R_i}{t}\times\frac{Y}{E}\right)^3 - 3\left(\frac{R_i}{t}\times\frac{Y}{E}\right) + 1} = \frac{10\ mm}{4\left(\frac{10\ mm}{4\ mm}\times\frac{40\ MPa}{70000\ MPa}\right)^3 - 3\left(\frac{10\ mm}{4\ mm}\times\frac{40\ MPa}{70000\ MPa}\right) + 1}$$

$$R_f = 10.043\ mm$$

b) Assuming you cannot change the material used, list 1 way you could reduce springback to improve the final part quality. **(5 minutes)**
2 pts total for a correct answer

- Pre-stretching the material/inducing tension stress. Springback is the result of nonuniform distribution of stresses in sheet thickness. Thus, additional stretch/tension force on the part can reduce this non uniform stress distribution and, consequently, the springback.
- Increasing initial radius (R_i)
- Decreasing thickness of material.
- Bend more than the R_i in a way to account for springback so when the springback does occur, the final radius us R_i (Called as Springback Compensation)

Note: The larger the relative bending radius (r/t), the lesser the degree of bending deformation, resulting in a smaller region of plastic deformation within the blank and a lesser degree of overall deformation. Hence, the proportion of plastic deformation in total deformation decreases, leading to larger springback.

c) Your engineering team suggests switching to 304 stainless steel (Young's Modulus 200 GPa, yield strength 200 MPa) as a way to reduce cost compared to aluminum. 304 stainless steel is available for \$1.25/kg, while it increases to \$2.50/kg for aluminum; however, aluminum is much less dense than steel (ρ_{Al} = 2.7 g/cm^3, ρ_{304} = 8.0 g/cm^3).

   i) Your first consideration is that part quality should not be affected by a material change, which means that you want to achieve the same or better degree of springback. Assuming the same initial radius of curvature for the bend, determine the minimum new thickness of the bracket. ***Note: for simplification, you can ignore higher order springback effects.*** **(5 minutes)**

   5 pts total: 2 correct use of springback equation (with or without cubic term), 1 for correctly using Rf from part a, 1 for correct new Y/E/t, 1 final answer

We know,

$$\frac{R_i}{R_f} = 4\left(\frac{R_i}{t} \times \frac{Y}{E}\right)^3 - 3\left(\frac{R_i}{t} \times \frac{Y}{E}\right) + 1$$

$$R_f \leq \frac{R_i}{4\left(\frac{R_i}{t}\times\frac{Y}{E}\right)^3 - 3\left(\frac{R_i}{t}\times\frac{Y}{E}\right) + 1} \leq \frac{R_i}{1 - 3\left(\frac{R_i}{t}\times\frac{Y}{E}\right)}$$

$$1 - 3\left(\frac{R_i}{t} \times \frac{Y}{E}\right) \geq \frac{R_i}{R_f}$$

$$3\left(\frac{R_i}{t} \times \frac{Y}{E}\right) \leq 1 - \frac{R_i}{R_f}$$

$$\left(\frac{R_i}{t}\right) \leq \frac{E}{3Y} - \frac{ER_i}{3YR_f}$$

$$\left(\frac{R_i}{\frac{E}{3Y} - \frac{ER_i}{3YR_f}}\right) \leq t$$

$$t \geq \left(\frac{R_i}{\frac{E}{3Y} - \frac{ER_i}{3YR_f}}\right) \qquad t \geq \left(\frac{10\ mm}{\frac{200{,}000\ MPa}{3\ (200\ MPa)} - \frac{(200{,}000\ MPa)(10\ mm)}{3(200\ MPa)(10.043\ mm)}}\right)$$

$$t \geq \left(\frac{10\ mm}{\frac{200{,}000\ MPa}{3\ (200\ MPa)} - \frac{(200{,}000\ MPa)(10\ mm)}{3(200\ MPa)(10.043\ mm)}}\right)$$

$$t \geq 7\ mm$$

ii) Assuming the rest of the part geometry (namely, the area of all surfaces orthogonal to the sheet thickness) is unchanged, determine the ratio of the material cost per part with aluminum compared to 304 stainless steel. Does it appear feasible to make a change in material? **(10 minutes)**

6 pts total: 2 for volume = SA * thickness, 1 for converting volume to mass for AL (in terms of SA), 1 for converting to mass for SS, 1 for cost multiplication, 1 for final answer.

We know, Surface Area (SA) is the same for both before and after material change.

$$Aluminum\ Cost\ =\ (\ SA\ \times\ Thicknesss_{Al}\ \times\ \rho_{Al}\ \times\ \$2.5/kg)$$

$$Aluminum\ Cost\ =\ (\ (SA\ m^{2})\ \times\ (4\ \times\ 10^{-3}\ m)\ \times\ 2700\ kg/m^{3}\ \times\ \$2.5/kg)$$

$$Aluminum\ Cost\ =\ \$27SA$$

$$Steel\ Cost\ =\ (\ SA\ \times\ Thicknesss_{Steel}\ \times\ \rho_{steel}\ \times\ \$1.25/kg)$$

$$Steel\ Cost\ =\ (\ SA\ \times\ (7\ \times\ 10^{-3}\ m)\ \times\ 8000\ kg/m^{3}\ \times\ \$1.25/kg)$$

$$Steel\ Cost\ =\ \$70\ SA$$

$$\frac{Steel\ Cost}{Aluminum\ Cost}\ =\ \frac{\$70SA}{\$27SA}\ \simeq\ 2.59$$

Assuming no other measures are taken to counteract springback, the proposed material change from Aluminum to Steel will require steel to be thicker (t ~7mm) to have the same level of spring back as aluminum (t ~ 4mm). However to make this part with thicker steel, it will be ~ 2.59 more expensive, so changing material to steel does not seem like a feasible option.

d) The initial mold designs require 7 bending operations to achieve the final shape. However, your engineers come to you with a new set of mold designs, which reduces the process to 5 bends. However, switching to this new tooling requires an additional cost of $25,000, incurred for every 500,000 units produced.

Assume the following for a given factory:

Annual demand (parts)	1 million
Labor cost ($/hr)	$20
Average hrs/week/worker	35
Average weeks/yr/worker	48
Cycle time per bending step	6 seconds

i) How many workers do you need to meet production demand, assuming 7 bending steps are needed? How many workers do you need if 5 bending steps are needed? **(10 minutes)**

7 pts total: 1 for calculation of available hours per worker, 1 for part cycle time for 5 steps, 1 for part cycle time for 7 steps, 1 for necessary annual hours for demand for 5 steps, 1 for annual hours for demand for 7 steps, 1 final answer for 5 steps, 1 final answer for 7 steps

$$Average\ available\ hours/yr/worker\ = 35\ hrs/week\ \times\ 48\ weeks/yr$$

$$Average\ available\ hours/yr/worker\ = 1680\ hrs/yr\ = 6048000\ s/yr$$

$$Cycle\ Time\ for\ 7\ bending\ steps\ part\ =\ 7\ steps\ \times\ 6\ s/step\ =\ 42s$$

$$Cycle\ Time\ for\ 5\ bending\ steps\ part\ =\ 5\ steps\ \times\ 6\ s/step\ =\ 30s$$

$$No\ of\ workers\ needed\ 7\ bending\ steps\ = \frac{(10^6\ parts/yr)\ (42s/part)}{6048000\ s/yr/worker} = 6.94\ = 7\ workers$$

$$No\ of\ workers\ needed\ 5\ bending\ steps\ = \frac{(10^6\ parts/yr)\ (30s/part)}{6048000\ s/yr/worker} = 4.96\ = 5\ workers$$

ii) Will the new tooling pay for itself within one year? **(10 minutes)**

7 pts total: 2 converting 7 workers to cost, 2 converting 5 workers to cost, 1 for calculating labor cost difference, 1 for total tooling cost (2 tool changes), 1 for final answer.

$$Tool\ Change\ Costs/yr\ =\ \$25,000/tool\ change\ \times \frac{1\ tool\ change}{500{,}000\ units}\ \times 10^{6}\ units\ =\ \$50,000$$

$$7\ steps\ worker\ cost/yr\ =\ 7\ workers\ \times 1680\ hr\ \times \$20/(hr\ worker)\ =\ \$235,200$$
$$5\ steps\ worker\ cost/yr\ =\ 5\ workers\ \times 1680\ hr\ \times \$20/(hr\ worker)\ =\ \$168,000$$

$$Cost\ Saved/yr\ =\ \$235,200\ -\ \$168,000\ =\ \$67,200$$

Therefore, since the cost saved is more than the cost of tooling, the tooling will pay for itself over the span of one year.

Problem 3 - Casting (24 points) (20 minutes)

Inspect the glue gun barrel provided with your exam (ignoring the darker polymer section and focusing only on the metal part).

a) Is this part die cast or sand cast? How can you tell? **(5 minutes)**

3 pts total: 1 correct answer, 2 for ID'ing surface finish and ejector pin marks

The part is made from die casting; the telltale sign is that ejector pin marks were clearly visible on the physical part.

b) Estimate the cooling time, both for the cases where the part is die cast and sand cast. Assume a coefficient of C = 1,200,000 s/mm^2 for sand casting and C = 80 s/mm for die casting. Assume the volume is 100cm^3 and the surface area is 500cm^2. **(5 minutes)**

5 pts total: 1 correct V/A, 1 correct exponent die, 1 correct exponent sand, 1 final answer die, 1 final answer sand

Sand Casting

$$t = 1200000\ (s/mm2)(\frac{V}{A})^2 = 1200000\ (s/mm^2)(\frac{100\ cm^3}{500\ cm^2} \times 10\ mm/cm)^2$$

$$= 4,800,000s = 1,333\ hrs$$

Note that this number is absurd; this resulted from students being provided the wrong value of the sand casting constant, and the actual expected time will be a factor of about 10,000 less.

Die Casting

$$t = 80\ (s/mm)(\frac{V}{A}) = 80\ (s/mm)(\frac{100\ cm^3}{500\ cm^2} \times 10\ mm/cm) = 160s$$

c) A critical part of avoiding quality issues during casting is to limit the turbulence of flow when injecting molten aluminum into the mold. Qualitatively (no need to make any calculations), list 2 ways how you can reduce the possibility of short shot without increasing flow velocity.
(3 minutes) 4 pts total: 2 per correct answer

- Increase runner diameter (which may also make it turbulent)
- Heat molten material to a higher temperature
- Add in insulation in die to minimize heat transfer (approach adiabatic conditions)
- Decrease length that molten metal needs to travel (may result in some design changes)
- Use a die material with lower thermal diffusivity (α)

d) The glue gun manufacturer wants to explore the possibility of making this barrel using powder bed fusion instead of casting. You do not have much information about the specific demand or costs of the manufacturer, but you can inform them generally about the tradeoffs between manufacturing processes.

Fill out the table below to qualitatively compare die casting and powder bed fusion to sand casting in terms of quality, cost, rate, and flexibility. We are not looking for very detailed information; just a brief assessment as to whether each process would be better or worse than sand casting with all other factors being equal, and 1 sentence as to why. **(7 minutes)**

12 pts total: 0.5 per correct choice, 1 per rationale

Mfg Tenet	**Sand Casting**	**Die Casting**	**Powder Bed Fusion**
Quality	-	*Compare to sand cast* ***(circle one)*** **Better**/**Worse**	*Compare to sand cast* ***(circle one)*** **Better**/**Worse**
		Brief Rationale Sand casting surface finish is rougher relative to parts produced by die casting as especially because surface texture of sand is uneven and leaves an imprint on the part. For die casting, since the part interacts with the smooth walls of the die, the surface finish is better. There are also higher chances of low dimensional accuracy due to shrinkage, and porosity/defects in sand casting.	*Brief Rationale* Even though the quality of powder bed fusion is subject to many variables like print rate, temperature of laser, etc, it generally produces parts that can be controlled better by fine tuning these variables. This is different to sand casting where the porosity, defects, and surface finish are harder to control directly by tuning the process parameters of the machine.
Cost	-	*Compare to sand cast* ***(circle one)*** **Better**/**Worse**	*Compare to sand cast* ***(circle one)*** **Better**/**Worse**
		Brief Rationale Die casting is more expensive than sand casting as more expensive mold (built using metal that has higher temperature than common cast metals like brass and 6061). Sand casting patterns are quite cheap to make and the sand itself is also relatively cheap to procure.	*Brief Rationale* For a mass produced part like the glue gun barrel, powder bed fusion would be much more expensive to use since both the metal powder and the rate limitation of the printer would keep costs of total parts produced higher relative to using sand casting.
Rate	-	*Compare to sand cast* ***(circle one)*** **Better**/**Worse**	*Compare to sand cast* ***(circle one)*** **Better**/**Worse**
		Brief Rationale	*Brief Rationale*

		Die casting has a lower cycle time as less preparation (preparing and packing the sand in the mold takes time). Also die casting cooling time is usually smaller relative to sand casting.	Powder bed fusion is very must rate limited as each layer of the part gets sintered one at a time. This is much slower to a process like sand casting where the entire part gets made at once.
Flexibility	-	*Compare to sand cast* ***(circle one)*** **Better/Worse**	*Compare to sand cast* ***(circle one)*** **Better/Worse**
		Brief Rationale Die casting has a worse level of flexibility compared to sand casting as the die casting mold is very expensive to make relative to patterning in sand casting. Therefore, changing part design can be quite expensive in die casting as new mold needs to be made.	*Brief Rationale* Powder bed fusion has higher flexibility relative to sand casting as any geometry/shape can be 3D printed with no tooling change costs. Since changing geometry/part design is just as simple as uploading a new 3D model on the slicing software, minimal additional cost is needed to change design/part geometry. On the other hand, there are some costs especially in making new patterns that are present in sand casting.

(clean chart for ABET, Josh 6/24)

Mfg Tenet	**Sand Casting**	**Die Casting**	**Powder Bed Fusion**
Quality	-	*Compare to sand cast* ***(circle one)*** **Better/Worse**	*Compare to sand cast* ***(circle one)*** **Better/Worse**
		Brief Rationale .	*Brief Rationale*
Cost	-	*Compare to sand cast* ***(circle one)*** **Better/Worse**	*Compare to sand cast* ***(circle one)*** **Better/Worse**
		Brief Rationale	*Brief Rationale*
Rate	-	*Compare to sand cast* ***(circle one)*** **Better/Worse**	*Compare to sand cast* ***(circle one)*** **Better/Worse**
		Brief Rationale	*Brief Rationale*
Flexibility	-	*Compare to sand cast* ***(circle one)*** **Better/Worse**	*Compare to sand cast* ***(circle one)*** **Better/Worse**
		Brief Rationale	*Brief Rationale*

MIT 2.008 Design and Manufacturing II

Quiz 2 - Part B, Take-Home Component

Spring 2024

Due: May 10th, 2024, by 2:00 PM ET

- This portion of the exam is open book/notes (since we cannot monitor you), but you are expected to work on it individually and cannot collaborate with classmates.
- All work for CREDIT must be completed in this quiz document.
- Please contact the TAs via Slack if you have any questions or difficulties.
- We will NOT be granting extensions for this portion of the exam, once you have received it. If you anticipate any difficulties with completing this question on time, please inform the TAs prior to picking this component up; within reason, we will arrange to send it to you exactly 48 hours before you need to submit it.

General Notes

- *For qualitative answers, we're not looking for long essays. Please answer using short (1-2 sentence per answer) bullet points.*
- *For quantitative answers, show your work as clearly as possible. When possible, keep answers in algebraic form until plugging in numbers at the very end; this way, it is much easier for graders to understand where you make mistakes and provide meaningful feedback **(and partial credit)**.*

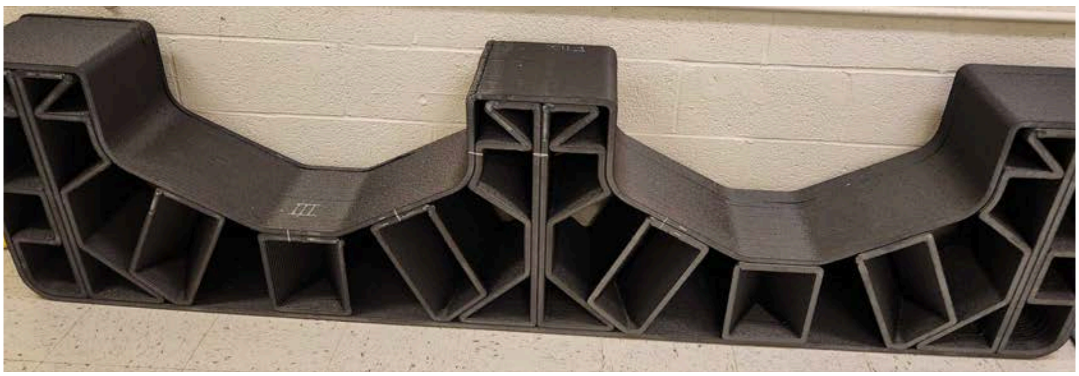
Name: ___________________________

Part A, In-Class Component		
Problem 1		Out of 15 points
Problem 2		Out of 31 points
Problem 3		Out of 24 points
Part B, Take-Home Component		
Problem 4		Out of 30 points
Total		**100 points**

Problem 4 - Manufacturing Systems Analysis (30 points) (50 minutes)

One proposed solution to the nearly 2 billion homeless or poorly housed people in the world is to create low-cost, rapidly and sustainably manufactured homes using recycled polymers. A study of candidate materials suggests that PET-GF (polyethylene terephthalate and glass fiber composite) would be ideal given both its abundance and material properties. It has further been proposed that this goal could be met using large scale additive manufacturing. You propose setting up a small factory based around extrusion using the Big Area Additive Manufacturing (BAAM) 3D printer from Cincinnati Incorporated.

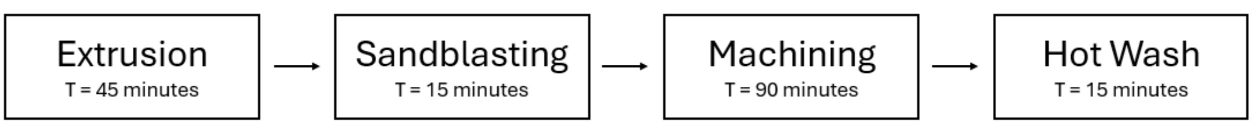
To simplify setting up a production line for this process, we will focus on one module: a foundation structure for the home (example photo below).



Assume that you have an abundance of PET-GF available, and that it is ready for use as 3D printer material. The production line is arranged according to the following steps:

- Printing
- Breakaway support removal using sandblasting
- Surface smoothing and finishing using CNC machining
- Excess support and contaminant removal using hot washing

A block diagram of these steps along with their efficiency metrics is provided below:



Station	Tau (min)	MTTR (min)	MTTF (min)	P (parts/min)
Extrusion	45	240	2880	0.02051
Sandblast	15	60	720	0.06154
Machine	90	180	1440	0.00988
Hot Wash	15	60	600	0.06061

a) What is the production rate of the line, assuming a scenario with no buffers between operations? **(3 minutes)**

2 pts total: 1 for use of Buzacott's formula, 1 final answer

Use Buzacott's zero-buffer line formula. Max cycle time is for machining:

$$P = \frac{1}{\tau_{max}} \frac{1}{1+\sum_{i=1}^{4} \frac{MTTR_i}{MTTF_i}} = \frac{1}{90} \frac{1}{1+\frac{240}{2880}+\frac{60}{720}+\frac{180}{1440}+\frac{60}{600}} = 0.0080\, parts/min = 0.479\, parts/hour$$

b) If you had the option to place a single infinite buffer in this manufacturing line, where would you place it and why? What will be your production rate after placing this buffer? **(10 minutes)**

4 pts total: 2 for identifying pre-bottleneck placement, 1 for use of Buzacott's formula on both sides of buffer, 1 final answer

Note that the set of machines on each side of the infinite buffer effectively form their own zero-buffer production line (where Buzacott's formula will apply). Also note that in a production line with an infinite buffer, the production rate will be the rate of the bottleneck "machine"; we want to place the buffer such that this production rate is maximized.

Intuitively, since the machining operation is the process bottleneck and we want to make sure that it is never starved, we want to place the buffer after sandblasting and before machining.

If we place the buffer after extrusion,

$$P_{before} = P_{extrusion} = 0.0205\, parts/min$$

$$P_{after} = \frac{1}{\tau_{max}} \frac{1}{1+\sum_{i=1}^{3} \frac{MTTR_i}{MTTF_i}} = \frac{1}{90} \frac{1}{1+\frac{60}{720}+\frac{180}{1440}+\frac{60}{600}} = 0.0085\, parts/min$$

$$P = min(P_{before}, P_{after}) = 0.0085\, parts/min$$

If we place the buffer after sandblasting,

$$P_{before} = \frac{1}{\tau_{max}} \frac{1}{1+\sum_{i=1}^{2} \frac{MTTR_i}{MTTF_i}} = \frac{1}{45} \frac{1}{1+\frac{240}{2880}+\frac{60}{720}} = 0.0190\, parts/min$$

$$P_{after} = \frac{1}{\tau_{max}} \frac{1}{1+\sum_{i=1}^{2} \frac{MTTR_i}{MTTF_i}} = \frac{1}{90} \frac{1}{1+\frac{180}{1440}+\frac{60}{600}} = 0.0091\, parts/min$$

$P = min(P_{before}, P_{after}) = 0.0091\, parts/min$

If we place the buffer after machining,

$$P_{before} = \frac{1}{\tau_{max}} \frac{1}{1+\sum_{i=1}^{3} \frac{MTTR_i}{MTTF_i}} = \frac{1}{90} \frac{1}{1+\frac{240}{2880}+\frac{60}{720}+\frac{180}{1440}} = 0.0086\, parts/min$$

$P_{after} = P_{wash} = 0.0606\, parts/min$

$P = min(P_{before}, P_{after}) = 0.0065\, parts/min$

The highest achievable production rate is 0.0091 parts/min, which happens if the infinite buffer is placed after the sandblasting operation.

c) Because of the high demand for affordable homes, investors funding a factory for this line insist that the production rate needs to get closer to the rate of the fastest machines; they are willing to invest in additional equipment to get closer to balancing the line.

i) Fill in the updated table of metrics below, assuming that investments are made so that during steady state production, every section of the line has the same cycle time. We have filled in some portions of the table already, to make it easier to check your work.

(5 minutes) 5 pts total: 0.5 for machines, 0.5 for cycle times, 1 each for r/p

Station	# machines	Tau (min)	MTTR (min)	MTTF (min)	p	r	e	P (parts/min)
Extrusion	3	15	240	2880	0.00521	0.0625	0.92308	0.06154
Sandblast	1	15	60	720	0.02083	0.25	0.92308	0.06154
Machine	6	15	180	1440	0.01042	0.08333	0.88889	0.05926
Hot Wash	1	15	60	600	0.025	0.25	0.90909	0.06061

ii) How does your answer to part b change with a more balanced line? Is your single infinite buffer placement different? What is your new production rate assuming this buffer? **(7 minutes)**

4 pts total: 2 for identifying bottleneck placement, 1 for use of Buzacott's formula on both sides of buffer, 1 final answer

The machining step is still the process bottleneck because it has the lowest efficiency; so at least for this line, the infinite buffer location will not change after balancing it.

If we place the buffer after extrusion,

$$P_{before} = P_{extrusion} = 0.0615\ parts/min$$

$$P_{after} = \frac{1}{\tau_{max}} \frac{1}{1+\sum_{i=1}^{3} \frac{MTTR_i}{MTTF_i}} = \frac{1}{15} \frac{1}{1+\frac{60}{720}+\frac{180}{1440}+\frac{60}{600}} = 0.0510\ parts/min$$

$$P = min(P_{before}, P_{after}) = 0.0510\ parts/min$$

If we place the buffer after sandblasting,

$$P_{before} = \frac{1}{\tau_{max}} \frac{1}{1+\sum_{i=1}^{2} \frac{MTTR_i}{MTTF_i}} = \frac{1}{15} \frac{1}{1+\frac{240}{2880}+\frac{60}{720}} = 0.0570\ parts/min$$

$$P_{after} = \frac{1}{\tau_{max}} \frac{1}{1+\sum_{i=1}^{2} \frac{MTTR_i}{MTTF_i}} = \frac{1}{15} \frac{1}{1+\frac{180}{1440}+\frac{60}{600}} = 0.0544\ parts/min$$

$$P = min(P_{before}, P_{after}) = 0.0544\ parts/min$$

If we place the buffer after machining,

$$P_{before} = \frac{1}{\tau_{max}} \frac{1}{1+\sum_{i=1}^{3} \frac{MTTR_i}{MTTF_i}} = \frac{1}{15} \frac{1}{1+\frac{240}{2880}+\frac{60}{720}+\frac{180}{1440}} = 0.0515\ parts/min$$

$$P_{after} = P_{wash} = 0.0606\ parts/min$$

$$P = min(P_{before}, P_{after}) = 0.0515\ parts/min$$

The highest achievable production rate is 0.0544 parts/min, which happens if the infinite buffer is placed after the sandblasting operation.

d) Conveniently, the investment in additional machines now makes it possible to represent the production line in Markov chain form, which means we can use our analytical MATLAB tools to analyze some additional decisions. Your investors are comfortable with diminishing profit given the altruistic nature of the project; however, they still want to ensure a profit of $1600 per simulation cycle to cover any overhead of running the factory.

Open up the long line program on Canvas and populate r and p with your values from part c.

Note: by default, the long line program does not include profit/cost calculations. However, you can paste in the following code beneath the long line script to compute estimates for revenue and inventory cost:

```
%Calculate hypothetical profit
pCoeff = 4000;    % Assume revenue of $4,000 per foundation
c = [50 70 100];      % Inventory holding cost per cycle
revenue = pCoeff*prodrate(1);
C_array = c.*nbar;
C_total = sum(C_array);
profit = revenue - C_total
```

After pasting these lines of code, your script in Canvas should look like this:

Script Reference Solution Save Reset MATLAB Documentation

```
% Input parameters:
% Change the values for k, r, p, and N
% Click "Run Script" to calculate prodrate and nbar
k = ;
r = ;
p = ;
N = ;

% Calculate deterministic processing time
[prodrate,nbar] = detlong(k,r,p,N)

%Calculate hypothetical profit
pCoeff = 4000;    % Assume revenue of $4,000 per foundation
c = [50 70 100];      % Inventory holding cost; modify this to fit the question
revenue = pCoeff*prodrate(1);
C_array = c.*nbar;
C_total = sum(C_array);
profit = revenue - C_total
```

Run Script

i) Firstly, suppose you can only place one buffer as in parts b and c, but this buffer must be finite. What is the maximum buffer size which still meets the profit target? What will be the average inventory in that buffer over a simulation cycle? **(10 minutes)**

4 pts total: 2 for setting up program correctly, 1 for choosing answer based on minimum $1600 profit, 1 for final answer

You may need to do some trial and error; but based on the parameters you have previously calculated, a buffer size of 30 exceeds $1600 profit and 31 falls below that target. So the optimal size is 30. At this point, nbar is about 18.23 units. We will also grant full credit if you add the amount in each buffer and get 23 units, since setting N1 and N3 equal to 4 is the result of a fault in the MATLAB program.

```
% Input parameters:
% Change the values for k, r, p, and N
% Click "Run Script" to calculate prodrate and nbar
k = 4;
r = [0.0625 0.25 0.08333 0.25];
p = [0.00521 0.02083 0.01042 0.025];
N = [4 30 4];

% Calculate deterministic processing time
[prodrate,nbar] = detlong(k,r,p,N)

pCoeff = 4000;    % Assume revenue of $5,000 per unit
c = [50 70 100];      % Inventory holding cost; modify this to fit the question
revenue = pCoeff*prodrate(1);
C_array = c.*nbar;
C_total = sum(C_array);
profit = revenue - C_total
```

```
prodrate =

    0.8118    0.8118    0.8118


nbar =

    2.6918   18.2254    2.0903


profit =

   1.6279e+03
```

```
% Input parameters:
% Change the values for k, r, p, and N
% Click "Run Script" to calculate prodrate and nbar
k = 4;
r = [0.0625 0.25 0.08333 0.25];
p = [0.00521 0.02083 0.01042 0.025];
N = [4 31 4];
```

```
prodrate =

    0.8125    0.8125    0.8125


nbar =

    2.6898   18.9109    2.0970


profit =

   1.5819e+03
```

ii) How does your answer change if, instead of a single buffer, you can have finite buffers after each production step? The foundation has roughly the same form factor after all post-extrusion steps, so assume that all finite buffers are the same size. **(5 minutes)**

3 pts total: 1 for setting up program correctly, 1 for choosing answer based on minimum $1600 profit, 1 for final answer

The largest number which maintains $1600 profit, assuming all buffers are the same size, is when N = 15. Here, the average inventory is 11.17 units after extrusion; 7.65 units after sandblasting; and 6.05 units after machining; for a total of 24.86 units (slightly more than the previous question).

```
% Input parameters:
% Change the values for k, r, p, and N
% Click "Run Script" to calculate prodrate and nbar
k = 4;
r = [0.0625 0.25 0.08333 0.25];
p = [0.00521 0.02083 0.01042 0.025];
N = [15 15 15];
```

```
prodrate =

    0.8316    0.8316    0.8316


nbar =

   11.1700    7.6453    6.0470


profit =

   1.6279e+03
```

iii) Which of the two possibilities (3 smaller buffers or 1 larger buffer) is the better option which meets the profit target? **(2 minutes)**

2 pts total: 1 for basing answer on production rate, 1 for answer

The production rate for the single buffer is 0.8118 parts per 15 minutes, and 0.8316 parts per 15 minutes for the case with multiple buffers. For this particular production line, having multiple smaller buffers is better to maximize the rate.

iv) One of your vendors comes to you with an extrusion barrel with a larger feed throat, which makes it much easier to clean excess polymers out of the barrel. As a result, your MTTR for the extrusion process is cut in half, from 4 hours all the way down to 2 hours. Assuming you have space for 3 identically sized finite buffers on your line, what is your new optimal buffer size, after making this upgrade? **(3 minutes)**

2 pts total: 1 for changing r correctly, 1 for answer

With the shorter MTTR, r1 changes from 0.0625 to 0.125. Re-running the program with this change, the largest number which maintains $1600 profit, assuming all buffers are the same size, is when N = 13 instead of 15. This makes sense because with the BAAM less likely to be down, less WIP should be necessary to keep the line running.

```
% Input parameters:
% Change the values for k, r, p, and N
% Click "Run Script" to calculate prodrate and nbar
k = 4;
r = [0.125 0.25 0.08333 0.25];
p = [0.00521 0.02083 0.01042 0.025];
N = [13 13 13];
```

```
prodrate =

    0.8396    0.8396    0.8396


nbar =

   10.6427    7.5495    5.8633


profit =

   1.7114e+03
```

e) Having not actually built the factory yet, your investors want to explore 2 alternatives for this line before spending money on equipment:

- Still invest in the extrusion-based BAAM but switch to a larger default nozzle size
- Base the production line on a large photopolymerization process instead of extrusion

Very briefly, provide one benefit and one tradeoff of each decision. **(5 minutes)**

4 pts total: 1 for each benefit, 1 for each tradeoff

Change 1: Larger nozzle size

Benefit:	• Decreased cycle time since each layer can be printed faster. (higher volumetric flow rate of extruded material)
Tradeoff:	

	• Need more thermal power to print extruded material as the volume coming out of the nozzle is larger. • Thermal management/cooling needed to deal with more thermal power. • Nozzle/various parts wear quicker due to more power/heat. • More power is needed to move a larger nozzle/gantry around the build platform. • Higher chance of uneven cooling/warping/delamination of printed layers since it has larger volume. • Harder to print fine/smaller features.

Change 2: Shift to photopolymerization line

Benefit:	• Higher quality and resolution of prints. • Possible to make fine features even in large structures as feature size is determined by laser diameter.
Tradeoff:	• Very high cycle time needed since the number of lasers can only be scaled so much before power needed becomes too much to make large prints. • Very high cycle time needed since laser diameter can only be scaled so much before beams start to diverge. • Large resin tank is needed to print large structures which may be expensive to keep in a controlled state (light exposure, temperature, humidity, etc) • Higher chance of crack propagation/fatigue failure, especially in large structures made from photopolymerization.