2/3 MIT 2.008 Design and Manufacturing II

Quiz 2 - Part A, In-Class Component

Spring 2025
May 7th, 2025

- 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 sentences 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)****.*
- *Each subquestion (e.g. a, b, c) may have a few parts to it (****i, ii, iii****). Make sure you r****ead and answer all parts of the question.***

Name: ____________________________

Part A, In-Class Component		
Problem 1		Out of 14 points
Problem 2		Out of 50 points
Problem 3		Out of 16 points
Part B, Take-Home Component		
Problem 4		Out of 20 points
Bonus		Out of 5 points
Total		**105 points**

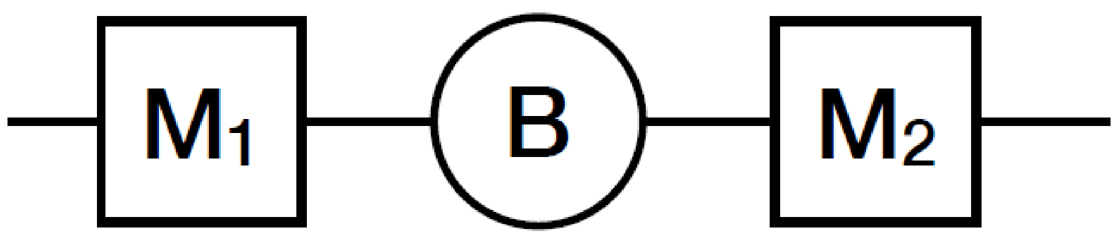
Problem 1 - Short Answers (14 points) (13 minutes)

a) In general, to the first order, the amount of springback in a sheet-metal bending process **increases** with **(low/high)** thickness, **(low/high)** yield strength, and **(low/high)** Young's modulus.
3 pts, 1 pt for each correct answer

b) For the following semiconductor processes, determine (mark with a check ✔) whether the process is considered subtractive, additive, or neither:
5 pts, 0.5 pt for each correct answer, 0.25 pt if they choose the alternate answer (in orange)

Process	Subtractive	Additive	Neither
Wet Etching	✔		
Physical Vapor Deposition		✔	
Oxidation		✔	✔
Ion Implantation		✔	✔
Lithography			✔
Metallization		✔	
Planarization (CMP)	✔		
Dry Etching	✔		
Doping and Diffusion		✔	✔
Characterization (e.g. surface profiling)			✔

c) Consider the deterministic two-machine line with an **infinite buffer** in between.



	M1	M2
Operation time (hours)	1	0.1

MTTR (hours)	100	100
MTTF (hours)	100	100

Consider the following changes **one at a time**, how would doubling each parameter affect the **overall production rate** of the line?
Provide **quantitative answers**, e.g. 0.5x, 0.67x, 1x, 1.33x, 2x, etc. of the original production rate.

6 pts, 0.5 pt for each correct answer and 0.5 pt for each valid rationale.

With infinite buffer, the production rate is determined by the production rate of the bottleneck. Since the operation time of M1 is 10x longer than the operation time of M2, M1 will remain as the bottleneck with any single 2x change in the parameters.

$$P = \frac{e_1}{\tau_1} = \frac{1}{\tau_1}\frac{MTTF_1}{MTTF_1 + MTTR_1}$$

Machine 1 Operation time DOUBLES	**Production rate:**_**0.5x**_
Brief rationale	Machine 1 is the bottleneck. Thus, the operation time directly affects the production rate inversely.

Machine 1 MTTR DOUBLES	**Production rate:**_**0.67x**_
Brief rationale	Machine 1 is the bottleneck. Original efficiency is 100/(100+100) = 0.5 New efficiency is 100/(100+200) = 0.33 Therefore, the new production rate is 0.33/0.5 = 0.67x the old production rate.

Machine 1 MTTF DOUBLES	**Production rate:**_**1.33x**_
Brief rationale	Machine 1 is the bottleneck. Original efficiency is 100/(100+100) = 0.5 New efficiency is 200/(100+200) = 0.66 Therefore, the new production rate is 0.66/0.5 = 1.33x the old production rate.

Machine 2 Operation time DOUBLES	**Production rate:**_**1x**_
Brief rationale	Machine 2 is not the bottleneck, even after

	doubling operation time. Due to the infinite buffer, changing machine 2 operation time will not change the line production rate.

Machine 2 MTTR DOUBLES	**Production rate:**_**1x**_
Brief rationale	Machine 2 is not the bottleneck, even after doubling MTTR. Due to the infinite buffer, changing machine 2 MTTR will not change the line production rate.

Machine 2 MTTF DOUBLES	**Production rate:**_**1x**_
Brief rationale	Machine 2 is not the bottleneck, and will be even less so with doubling MTTF. Due to the infinite buffer, changing machine 2 MTTf will not change the line production rate.

Problem 2 - Forming and Casting (50 points) (46 minutes)

Display technologies have progressed from CRT and LCD to OLED and now to MicroLED. While OLED displays use organic molecules deposited through solution-based processes to create light-emitting pixels, MicroLED displays utilize inorganic III-V semiconductor materials. These are typically grown on separate wafers for red, green, and blue emission, as each material system is optimized for a different wavelength.

In the MicroLED process, these emitter chips are **singulated** (cut into individual dies) and then **transferred onto a transistor matrix** that acts as the active backplane, controlling pixel operation—illustrated schematically in **Figure 1**.

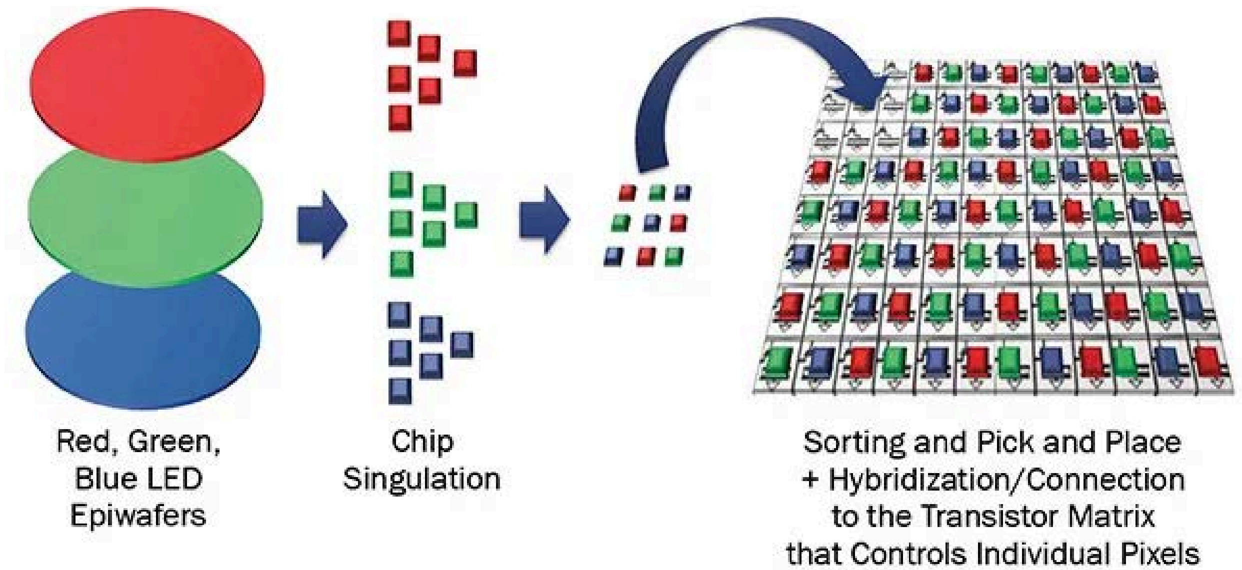


Figure 1. MicroLED pixel integration process. Singulated red, green, and blue MicroLED dies, each fabricated on separate III-V wafers, are picked and transferred onto a transistor matrix to form a full-color display.

Unlike conventional Front-End-Of-Line (FEOL) processes discussed in class, this step belongs to the **Back-End-Of-Line (BEOL) packaging**. This is an area where we **mechanical engineers can contribute**, especially in the precision mechanisms involved in chip transfer.

The **flip chip transfer process**, shown in **Figure 2**, includes a **vacuum head** that picks up singulated MicroLEDs, a **bond arm** that moves and positions the dies, and **rotating motors** that provide the necessary degrees of freedom for alignment. The MicroLED die is then flipped and bonded such that its top-side contacts align with the interconnects on the top of the transistor matrix.

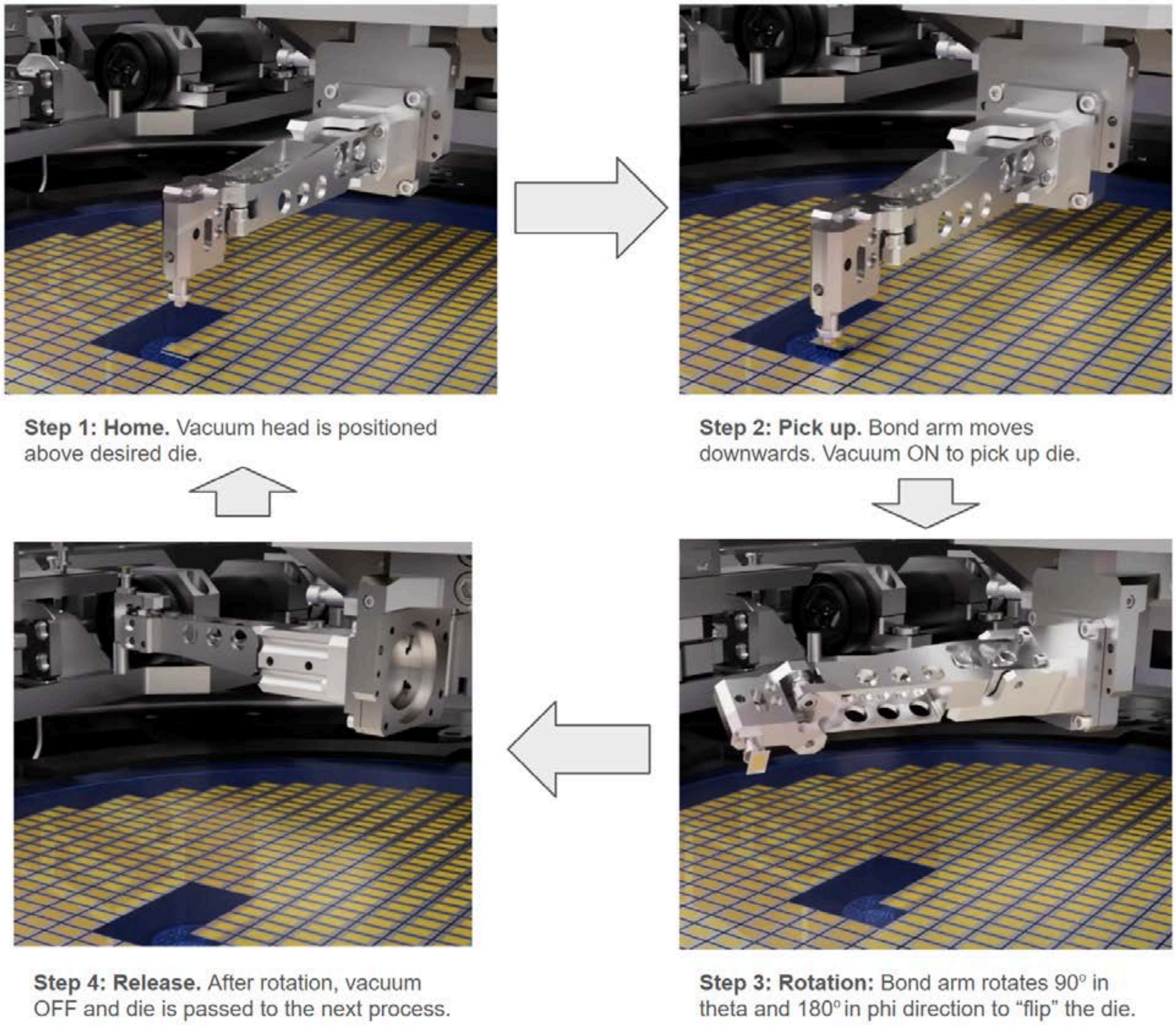


Figure 2. Schematic of the flip chip transfer process.

For this question, we focus on the **bond arm**, modeled as a beam with a constant **H-shaped cross-section**, shown in **Figure 3**. Assume the beam is currently manufactured using **machining**. Disregard mounting and joint details for now.

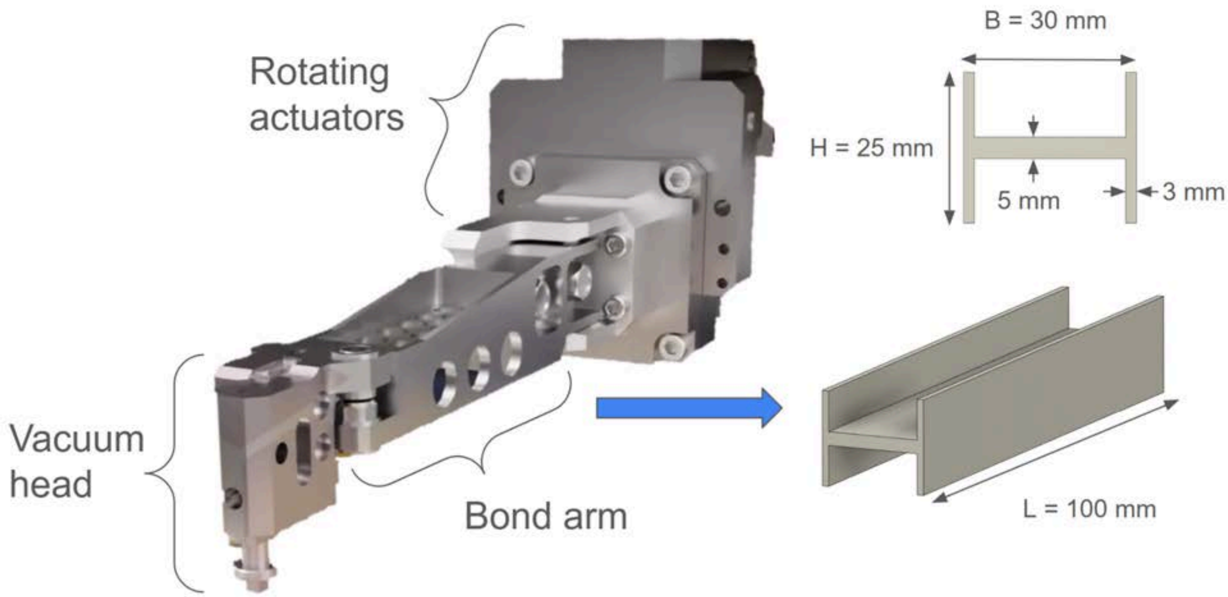


Figure 3. Flip chip assembly (left) showing a vacuum head to pick up the MicroLED die, a bond arm to position the die, and rotating motors to assist with alignment. **The simplified bond arm (right)** modeled as a beam with an H-shaped cross-section, assumed to be fabricated by machining.

a) Process Comparison: Bond Arm Manufacturing

Your task is to propose and evaluate alternative manufacturing methods for producing the bond arm beam used in flip-chip transfer tools. Focus on four manufacturing processes:

- Metal extrusion
- Sheet metal bending
- Forging
- Die-casting

Design Objective. Design a cross-section for each process that is:

- Relatively lightweight
- Structurally rigid in bending

While an H-shaped cross-section (as shown in Figure 3) is a natural choice, other viable options include U-shaped, T-shaped, or hollow rectangular sections. Solid bars are not desirable due to weight constraints in high-speed precision assembly.

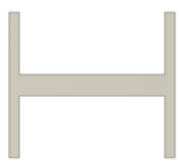
Instructions. For each process, do the following:

1. **Sketch** the cross-section suitable for that manufacturing method.
2. Describe **key geometric features** that make the design manufacturable, such as:

    a. Wall thickness and thickness ratios
    b. Corner treatments (rounds, fillets, chamfers)
    c. Tapering or draft angles, if applicable
3. Explain your **rationale:** Why are these features necessary or optimal for the process?
4. Evaluate process **suitability for producing beams of approximate dimensions L=100 mm, B=30mm, and H=25mm**, as shown in Figure 3, from an **aluminum alloy.**
5. Comment on:
    a. Expected **part quality** (e.g., surface finish, mechanical properties, defect risk)
    b. Major **cost contributors** (tooling, material waste, cycle time, etc.)
    c. **Cost effectiveness at different production volumes** (low vs. high quantity)

Reference Example. A complete example is provided for the case of machining. You may frame your other answers relative to the machining example if helpful.

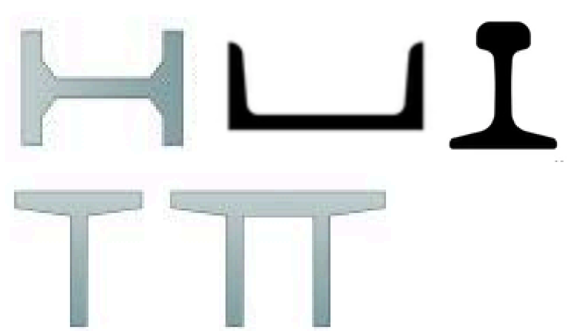
Machining (Reference Example Analysis)

Sketch **Cross section** Describe key geometric features (wall thickness, corners, angles) Explain how the above features contribute to **manufacturability**	 ● A beam with **H-shaped cross-section** can be machined with an end mill in two fixturing positions (top and bottom) ● The **wall thicknesses** tend to be uniform for each wall but do not necessarily need to be the same between walls, as long as they are rigid enough to withstand the machining process without warping. ● **Rounds and fillets are not necessary** in between the middle and edge walls, but can be added using a ball or bull end mill. Chamfers on the outside edges are also optional ● **Tapering and draft angles are not needed** and complicates the machining process.  ● A **U-shaped cross-section is an alternative** choice that can be easily machined on a single fixture. ● In contrast, a **hollow (fully-enclosed) rectangle is not a viable option** since it will be difficult to machine with an end mill.
Suitability to produce **Aluminum** beams of	● Aluminum is readily machinable ● 100x30x25 mm is a good size for machining without extremely long

external dimensions **100x30x25 mm** (as shown in Fig. 3)	processing time. ● The target web and flange thicknesses of 5 mm and 3 mm, respectively, provide sufficient structural rigidity from deflecting machining process.
Quality (and performance)	● **Surface finish** can be made very fine, depending on the machining parameters used. ● **Mechanical performance** should be decent as the stock material is expected to be free from defects. However, the grain alignment may not favor the specific loading case.
Major **cost** contributor(s)	● **Material cost:** a **large contributor** since we are starting with a stock material with significantly more volume than the part. It is not economical or desirable to recycle the removed chips. ● **Overhead:** another **large contributor** due to the long processing time. Even for the simple structures shown above, we need to machine away a large volume of material, that has an associated cutting energy that needs time for a given cutting power. ● **Equipment:** potentially significant contribution to cost per part for low-volume production. **Less significant at high part quantity.** ● **Tooling:** the cost of the end mills are **not significant** assuming a lightweight, easily machinable aluminum material is used for part.
Cost effectiveness vs production volume	● **Machining** is cost-effective at **low production volumes** due to the high variable costs (material and overhead).

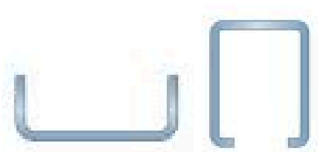
32 points total, 8 points for each process: 1 pt for sketch, 2 pts for manufacturability, 1 pt for suitability, 2 pts for quality, 2 pts for costs

Metal extrusion

Sketch **Cross section** Describe key geometric features (wall thickness, corners, angles) Explain how the above features contribute to **manufacturability**	 ● Assuming a **constant cross-section across the length of the beam**, a wide variety of shapes can be made with extrusion. ● The difference of the cross-section shape of the stock material and desired part would dictate the amount of force needed for extrusion (can be done in multiple rounds if needed). ● **Rounds and fillets** make it easier for the material to flow plastically while it is being extruded.

	• Wall thicknesses must be **uniform or gradually varied** to prevent flow defects.
Suitability to produce **Aluminum** beams of external dimensions **100x30x25 mm** (as shown in Fig. 3)	• Aluminum alloys are relatively ductile and are one of the most commonly extruded material. • 30x25 mm cross section is a suitable size to be made with an extrusion die. • Extrusion process can make long rods, which are then cut and machined to the desired length of 100 mm.
Quality (and performance)	• Moderate surface finish (improvable with post-processing). • Good dimensional consistency in long lengths. • Directional grain structure enhances **bending strength** along the axis
Major **cost** contributor(s)	• **Tooling cost** for the custom die is major cost contributor. • Equipment cost to apply the high force needed for extrusion. • Economical for **high-volume** production due to low per-unit cost. • Minimal material waste, so low material cost.
Cost effectiveness vs production volume	• **Effective at medium-high production volumes** due to decent upfront costs and low material cost (minimal waste).

Sheet metal bending

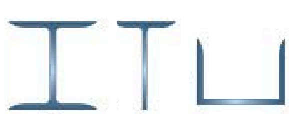
Sketch **Cross section** Describe key geometric features (wall thickness, corners, angles) Explain how the above features contribute to **manufacturability**	 • Must be derived from a **single flat sheet**, folded to shape. • Limitations in forming a true H-shape; can create a U-shape. • **Rounded corners** because bend radii required (typically ≥ material thickness). • **Wall thickness constant** across profile (dictated by sheet).
Suitability to produce **Aluminum** beams of external dimensions **100x30x25 mm** (as shown in Fig. 3)	• Aluminum is well suited for stamping and bending due relatively low yield strength but ductile nature. A high modulus-to-strength ratio is helpful to reduce springback. • Part dimensions of ~100 mm can be readily stamped and the 3 mm thickness can be bent with a radius of ~6mm.
Quality (and performance)	• Surface finish follows stock material • Weaker at joints and bends due to stress concentration. • Minimal internal reinforcement; risk of flexing under load.
Major **cost**	• **Overhead cost is major contributor** as metal bending is

contributor(s)	labor-intensive, but this shape is simple. ● **Moderate cost for equipment and tooling**. ● Low material cost.
Cost effectiveness vs production volume	● **Effective at low-medium production volume.** Overhead cost is the driving factor, while the equipment and tooling are fairly inexpensive (compared to the other processes).

Forging

Sketch **Cross section** Describe key geometric features (wall thickness, corners, angles) Explain how the above features contribute to **manufacturability**	 ● **Tapered** flanges and web. ● Rounded internal corners and tapering required for die release and material flow. ● Thickness variation possible (e.g., thicker flange, thinner web). ● Needs draft angles (~2° typical).
Suitability to produce **Aluminum** beams of external dimensions **100x30x25 mm** (as shown in Fig. 3)	● Similar to extrusion: aluminum alloys are relatively ductile and can be forged to desired shape ● Part dimensions of ~100 mm can fit in a forging die and processed without excessive force.
Quality (and performance)	● **Superior mechanical properties** due to directional grain flow. ● Excellent fatigue and impact resistance. ● Suitable for high-load applications requiring robustness. ● Secondary machining may be needed for precision surfaces.
Major **cost** contributor(s)	● **High tooling and equipment cost (dies and presses)** ● Low material cost (small amount of machining may be necessary to remove flash and create precise surfaces)
Cost effectiveness vs production volume	● **Effective at medium-high production volumes** due to decent upfront costs and low material cost (minimal waste).

Die-casting

Sketch **Cross section** Describe key	

geometric features (wall thickness, corners, angles) Explain how the above features contribute to **manufacturability**	• Requires **draft angles (~1–3°)** and **filleted corners**. • Thin walls feasible, but need **uniform wall thickness** to avoid shrinkage.
Suitability to produce **Aluminum** beams of external dimensions **100x30x25 mm** (as shown in Fig. 3)	• Aluminum alloys have relatively low melting point (compared to other metals) and good thermal conductivity, which makes them suitable and commonly used in die-casting • Part dimensions of ~100 mm can fit in a casting die and the 3 mm thickness should provide suitable cooling time (long enough to prevent premature solidification but short enough for high-volume production).
Quality (and performance)	• Allows complex hollow and ribbed profiles if needed. • Surface finish is good; internal porosity may limit structural strength. • Suitable for medium-strength, **precision-fit parts**, but not high-stress.
Major **cost** contributor(s)	• **High tooling and equipment cost (dies and presses)** • Low material cost (net-shape production)
Cost effectiveness vs production volume	• **Effective at high production volumes** due to high upfront cost and low material cost (minimal waste).

b) **Sheet metal stamping and bending.** You would like to create a bond arm with a U-shaped profile with dimensions shown in Fig. 4 using sheet metal stamping and bending.

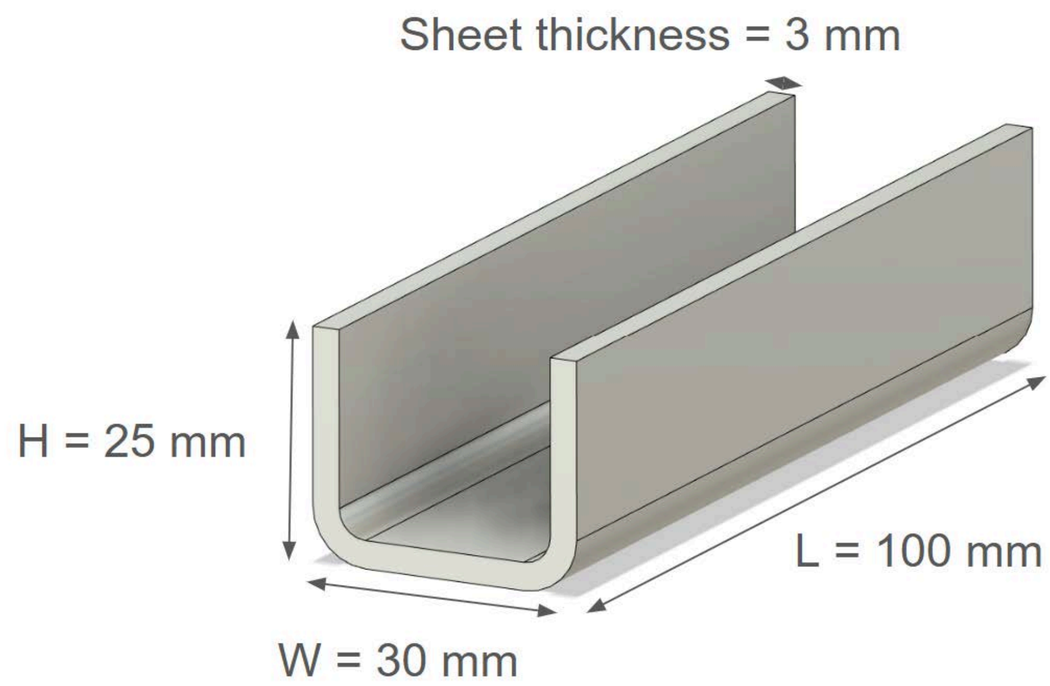


Figure 4. Bond arm made with sheet metal stamping and bending showing the desired part dimensions.

i) Using AL-5052 (properties in Appendix 1), what is the **shearing force** required for the stamping machine to create **one sheet** that is to be bent to the beam shown in Fig. 4?

3 pts, 1 pt for calculating area, 1 pt for correctly using UTS in the formula, 1 pt for correct shearing force.

To calculate the shearing force, we need to know the sheared surface area, which is the perimeter of the stamped material multiplied by its thickness.

Perimeter: 2*(25+30+25+100)= 360 mm

$$A_{shear} = Perimeter \times thickness = 1080\, mm^2$$

$$F_{shear} = \sigma_{UTS} \times A_{shear} = 230\, MPa \times 1080\, mm^2 = 248,400\, N \approx 250\, kN$$

ii) You successfully stamped and bent the aluminum 5052 sheet metal to the desired shape with barely acceptable springback. Your colleague then told you that we need to reduce the wall thickness to fit a larger module inside the cavity. To reduce the thickness without sacrificing bending stiffness, you thought of replacing AL-5052 with a Titanium alloy (Ti-6Al-4V) which has a higher Young's modulus. This way, you are able to reduce the thickness to 2 mm without reducing the bending stiffness of the beam. **Name and explain at least 2 issues** you might encounter in creating a beam with the outer dimensions shown in Fig. 4 using the same stamping and bending setup?

4 pts, 1 pt for each answer, 1 pt for explanation

1) Insufficient shear force
    (a) From Appendix 1, we see that Ti-6Al-4V has a UTS that is 5x higher than AL-5052. Thus, even with a thickness reduction from 3 to 2 mm, the shear force required to stamp out the titanium sheet metal will be much higher than that for the aluminum sheet metal.
2) More springback
    (a) From the springback equation, we can tell that the amount of springback increases with higher Y/hE. While the titanium alloy does have higher E value, it has significantly higher yield strength than the aluminum alloy. In addition, we have reduced the thickness of the sheet metal. As a result, we expect that there is more springback using the same sheet bending set up.
3) More weight
    (a) Acceptable answer because difference in density is more than difference in thickness

c) Die-casting.

i) Estimate the **cooling time** to die-cast a part following the dimensions shown in Fig. 4. Assume a coefficient of C = 80 s/mm.

2 pts, 1 pt for correctly determining thickness, 1 pt for calculating cooling time with die-casting cooling time formula.

Accept explicitly calculating volume and area to get V/A, plus excuse any minor differences due to different assumptions (e.g. including the edge area).

The equivalent V/A is half the thickness of the sheet = 1.5 mm.

Hence, the cooling time is t = C(V/A) = 80*1.5 = 120 s.

ii) After manufacturing the tool by die-casting aluminum 5052, you found that the bending stiffness is insufficient and discovered that the material is quite porous. Qualitatively (no need to make any calculations), list **2 possible causes for porosity and ways to address them.**

4 pts, 1 pt for each answer, 1 pt for a way to address each.

1) Air entrapment
    (a) High speed injection traps air
    (b) Turbulent flow
    (c) Addressed by reducing injection speed or runner diameter to ensure laminar flow. Can also add vacuum and venting channels to remove air
2) Shrinkage
    (a) Cooling and solidification shrinkage may cause porosity due to insufficient feed metal.
    (b) Addressed by ensuring uniform cooling and increasing injection/hold pressure/time.
3) Moisture or contamination
    (a) Presence of moisture and dust particles may create vapor and trap air inside the chamber
    (b) Addressed by cleaning the mold and ensuring dry mold by preheating

iii) Even after successfully addressing the porosity issue, the **stiffness of the beam is still inadequate**. Since the die-casting mold was expensive to make, you **do not wish to change the geometry** of the part. Instead, you thought of **changing the material to stainless steel** which has a much higher Young's modulus. List **2 potential issues** that may arise, in terms of **mechanical performance and die-casting** of the bond arm, from implementing this change. 4 pts, 1 pt for each answer, 1 pt for explanation

1) High melting temperature may not be suitable for die-casting
    (a) SS304 has much higher melting temperature than AL5052. Die-casting requires complete melting and flowing of the metal into the cavity. The higher melting point would increase the heating time and require a mold with even higher temperature resistance (melting point and dimensional stability) and may not be feasible
2) High density increases bond arm weight and affects performance
    (a) The bond arm needs to accelerate and settle quickly. Changing the material to steel, which has a much higher density than aluminum, would increase the weight of the bond arm, potentially disrupting the dynamic stability of the flip chip system and leading to higher power requirement of the rotation actuators.

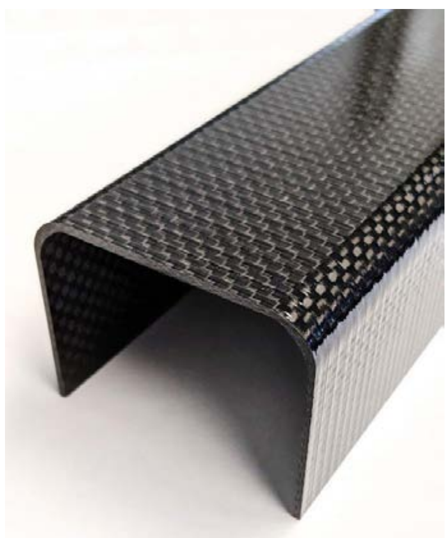
Problem 3 - Layered manufacturing (16 points) (15 minutes)

Your manager tasked you to come up with the next-generation bond arm with better dynamic performance than the current aluminum version. You consider using advanced materials including carbon fiber reinforced polymers and additive manufacturing with carbon fiber fillers.

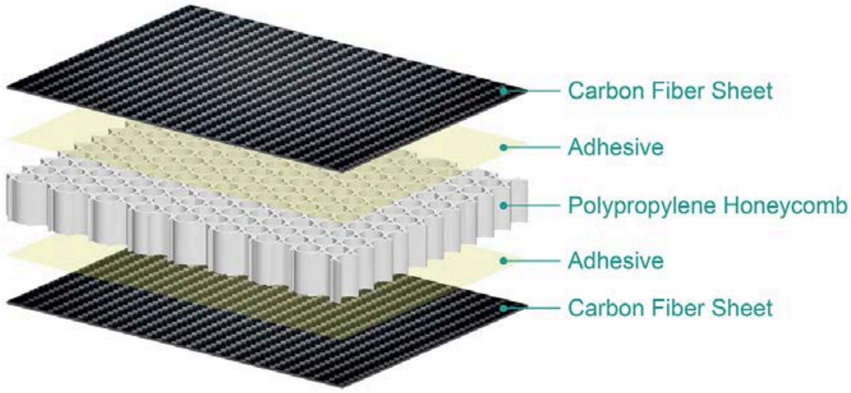
a) **Carbon Fiber Reinforced Polymer (CFRP)**. You decide to design the bond arm using carbon fiber composites, and are considering the geometry, fiber orientation, and expected performance benefit.

    i) **Geometry.** Would you keep a similar geometry to the aluminum bond arm, such as the H-beam (Fig. 3) or U-beam (Fig. 4)? Consider the shape and construction of carbon fiber sheets where they are commonly used (sports equipment and aerospace) and **sketch a suitable geometry and justify the design.** 4 pts, 2 pts for sketch, 2 pts for valid justification.

    - For the best performance, we prefer to have continuous fibers and minimize any cuts and ends.
    - In addition, as a layered manufacturing process, the walls should have relatively consistent thickness to ensure the fibers' continuity.
    - The H-beam and U-beam are feasible designs wherein the fiber fabric/prepreg can be laid onto a positive mold to form the negative features of the parts.



    - One common construction is the honeycomb sandwich, which would have high bending stiffness when the fiber sheets are in maximum tension and compression. However, this may not be suitable for a small part such as the bond arm.



- The ideal configuration for the bond arm would be similar to sporting goods such as a hockey stick, wherein the CFRP forms a fully enclosed tube. This structure would have good bending stiffness in both bending axis.

ii) **Performance gain.** What properties of CFRPs make them desirable alternatives to Aluminum and how would they improve the performance of high-speed precision assembly machines? 4 pts, 2 pts for each answer

1) Quasi-isotropic CFRP has comparable young's modulus to aluminum but comes at a much reduced density. Essentially, they have a **higher specific modulus.**
2) Hence, replacing aluminum with CFRP can yield **either reduced weight or increased stiffness**, depending on the geometry and volume of material used.
3) The resonant frequency of a structure is roughly proportional to the **square root of stiffness/mass**. This resonant frequency determines the dynamic behavior of

the structure. In high-speed precision equipment, a higher resonant frequency would result in higher placement accuracy and lower settling time.

b) Additive manufacturing.

i) Comparing the density and Young's modulus of CFRP vs 3D printing (FFF/FDM) nylon with carbon fiber fillers in Appendix 1 and recalling what you know about the FFF process, what can you determine about the **carbon fiber volume fraction** and **fiber length** between these two materials? Assume that epoxy and nylon has similar densities, while carbon fiber has a significantly higher density than these matrix materials. 4 pts, 2 pts for each answer.

1) **Lower carbon fiber volume fraction.** The 3D printing nylon with carbon fiber fillers has lower density. Since the density of carbon fiber ~1,800 is higher than that of polymers ~1,000, we can assume that the 3D printing nylon has lower (~30%) carbon fiber content than the CFRP epoxy prepreg material (~60%).
2) **Shorter fibers.** The 3D printing material has a lower Young's modulus due to having shorter chopped fibers. It is not possible to incorporate long fibers in 3D printing filament due to the limited diameter of the filament. Meanwhile, aligning the fiber along the length of the filament would be impractical.

ii) **Competitive advantage.** Considering the lower Young's modulus of 3D printing nylon when compared with CFRP and aluminum, additive manufacturing still has its merits. State and discuss at least **two benefits of additive manufacturing** to produce **bond arms for different machines** with different loads, actuator specifications, and dynamic requirements. 4 pts, 2 pts for each answer.

1) **Rapid prototyping.** Without the need to create molds that take time and money, additive manufacturing allows rapid prototyping of the bond arm design for testing to meet the functional requirements.
2) No need to create expensive molds everytime
3) **Flexibility.** It is much easier to implement changes to the part design in case there is any changes in the specifications or related modules.
4) **Combining multiple parts.** Additive manufacturing allows the production of certain geometries that are not possible by traditional manufacturing processes. This can lead to reduced part count and simplified process plans.
5) **Generative design.** We can customize the bond arm design to create the optimal geometry for each use scenario, leading to potentially better performance and reduced weight.

Appendix 1: Physical properties of several metal alloys

Property	**AL-5052**	**Ti-6Al-4V**	**Stainless Steel 304**	**Carbon Fiber Epoxy Comp. (Quasi-isotropic)**	**3D printing nylon with carbon fiber fillers**
Density (kg/m^3)	2,700	4,430	8,000	1,600	1,300
Young's modulus (MPa)	70,000	114,000	200,000	60,000	12,000
Yield Strength (MPa)	190	1,100	215	600	80
Ultimate Tensile Strength (MPa)	230	1,170	505	Brittle failure	90
Melting point (deg C)	600	1600	1400	Epoxy degrades at 300	240

MIT 2.008 Design and Manufacturing II

Quiz 2 - Part B, Take-Home Component

Spring 2025

Due: May 9th, 2025, by 5:00 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 sentences 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)****.*
- *Each subquestion (e.g. a, b, c) may have a few parts to it (****i, ii, iii****). Make sure you r****ead and answer all parts of the question.***

Name: ____________________________

Part A, In-Class Component		
Problem 1		Out of 14 points
Problem 2		Out of 50 points
Problem 3		Out of 16 points
Part B, Take-Home Component		
Problem 4		Out of 20 points
Bonus		Out of 5 points
Total		**105 points**

This take-home exam continues the discussion of the microLED manufacturing process from the in-class exam. Therefore, the introduction is repeated below for your reference:

Display technologies have progressed from CRT and LCD to OLED and now to MicroLED. While OLED displays use organic molecules deposited through solution-based processes to create light-emitting pixels, MicroLED displays utilize inorganic III-V semiconductor materials. These are typically grown on separate wafers for red, green, and blue emission, as each material system is optimized for a different wavelength.

In the MicroLED process, these emitter chips are **singulated** (cut into individual dies) and then **transferred onto a transistor matrix** that acts as the active backplane, controlling pixel operation—illustrated schematically in **Figure 1**.

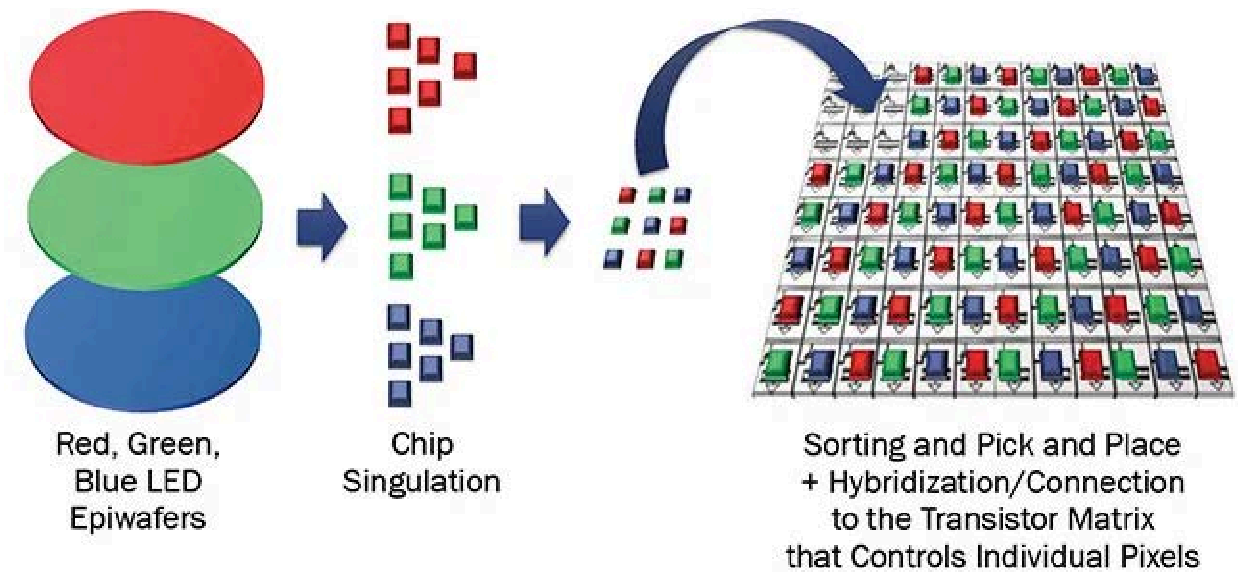


Figure 1. MicroLED pixel integration process. Singulated red, green, and blue MicroLED dies, each fabricated on separate III-V wafers, are picked and transferred onto a transistor matrix to form a full-color display.

Unlike conventional Front-End-Of-Line (FEOL) processes discussed in class, this step belongs to the **Back-End-Of-Line (BEOL) packaging**. This is an area where we **mechanical engineers can contribute**, especially in the precision mechanisms involved in chip transfer.

The **flip chip transfer process**, shown in **Figure 2**, includes a **vacuum head** that picks up singulated MicroLEDs, a **bond arm** that moves and positions the dies, and **rotating motors** that provide the necessary degrees of freedom for alignment. The MicroLED die is then flipped and bonded such that its top-side contacts align with the interconnects on the top of the transistor matrix.

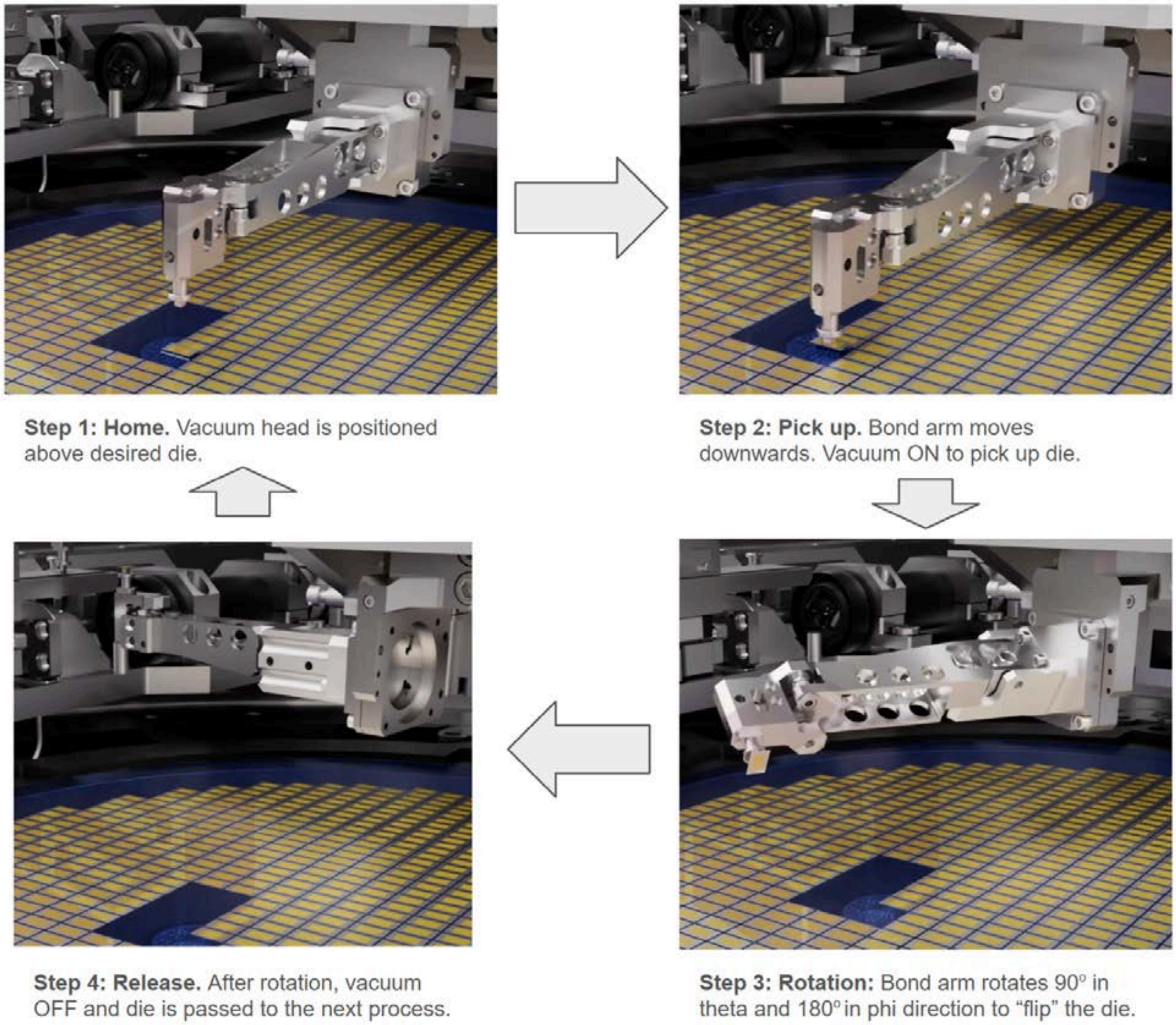


Figure 2. Schematic of the flip chip transfer process.

Problem 4 - Manufacturing Systems Analysis (20 points) (30 minutes)

One of the biggest challenges in microLED fabrication stems from the sheer number of individual dies that must be picked and placed onto the transistor pixel matrix. Each individual die is a single color of a single pixel. We shall analyze the production of these microLED displays and optimize the production rate.

a) Meeting the required number of dies.

   i) Calculate the number of dies needed for a full HD display (1920 pixels wide and 1080 pixels high) with full RGB (3 separate dies per pixel). 1 pt

      1) Number of dies: 3*1920*1080 = 6,220,800 dies ~ 6.2 million dies
      2) Accept answer for no of dies per color: 1920*1080 = 2,073,600 dies per color

ii) It takes 60 milliseconds (0.06 s) to complete a pick-and-place sequence (shown in Fig. 2) of a single die. How long would it take for a pick-and-place machine to assemble a single display? 2 pts, 1 pt for approach, 1 pt for right answer

1) Time per die = 0.06s
2) Dies per hour = 3600/0.06 = 60,000
3) Operation time = 6.2 million / 60,000 = 103.68 hours.

iii) Assume that each die is a square with a width of 50 microns (0.05 mm x 0.05 mm). Considering the die sawing line width and unusable edges, assume that 90% (yield) of the wafer area can be used as dies. Estimate the number of dies that can be produced from a 6-inch wafer. 1 pt for right answer

$$Total\ wafer\ area = \pi \times (75\ mm)^2 = 17,660\ mm^2$$

$$Area\ of\ each\ die = (0.05\ mm)^2 = 0.0025\ mm^2$$

$$Number\ of\ die\ per\ wafer = Yield \times \frac{Wafer\ area}{Die\ area} = 0.9 \times \frac{17,660}{0.0025} = 6.36\ million$$

iv) How many 6-inch wafers (integer number) are needed to produce the RGB full HD display? 1 pt for right answer

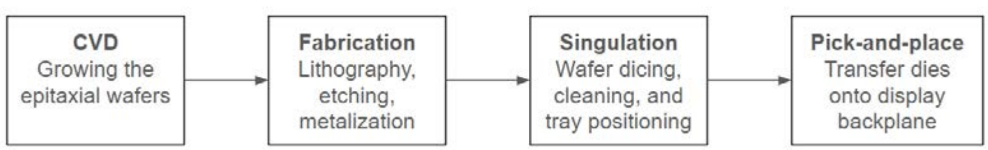
Any of the answers below is correct (non-integer numbers are accepted):

1) **Calculating die of all 3 colors together.** No. of wafers = number of dies/number of die per wafer = 6,220,800/6,360,000 = **0.977 ~ 1 wafer per display**

2) **Accept calculating dies for each color separately.** In that case. No of wafers = 2,073,600/6,360,000 = **0.326 wafer per color** per display

3) If separating colors and rounding up to integer number: 1 wafer per color per display -> **3 wafers** for 3 colors per display.

b) Now, we shall consider the whole manufacturing line shown in Fig. 1, using the process diagram below for the time it takes to make 1 display:



	CVD	Fabrication	Singulation	Pick-and-place
Tau (hrs)	3	15	1	103.68

MTTF (hrs)	300	300	100	300
MTTR (hrs)	30	60	10	60

i) Input the operation time for a single pick-and-place machine to manufacture one full HD RGB display panel, which you calculated in 4aii, into the table above. Assuming a scenario with no buffers between operations, what is the average time needed to produce 1 display?

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

Use Buzacott's zero-buffer line formula. Max operation time is for pick-and-place:

$$P = \frac{1}{\tau_{max}} \frac{1}{1+\sum_{i=1}^{4} \frac{MTTR_i}{MTTF_i}} = \frac{1}{103.68} \frac{1}{1+\frac{30}{300}+\frac{60}{300}+\frac{10}{100}+\frac{60}{300}} = 0.0060\ parts/hour$$

Time to make one display = 1/P = 165.89 hours = 6.9 days ~ 1 week!!

ii) You realize that the production rate is way too slow to meet demand. As such, you want to address the bottleneck to reduce its operation time and increase the overall production rate. What is the minimum number of pick-and-place equipment that we need to run in parallel to prevent it from being the only bottleneck in the system? 2 pts, 1 pt for correctly determining the next possible bottleneck, 1 pt for answer.

Operation time of a single pick-and-place machine: 103.68 hours
Operation time of the next possible bottleneck (fabrication): 15 hours
They have the same MTTR and MTTF

$$No.\ of\ machines\ needed = \frac{Operation\ time\ of\ one\ pick-and-place}{Operation\ time\ of\ fabrication} = \frac{103.68}{15} = 6.91\ machines$$

Round up to 7 machines

We would need at least 7 pick-and-place machines running in parallel to prevent it from being the only bottleneck in the system.

iii) What is the equivalent tau of running multiple pick-and-place machines in parallel, as you have calculated above? Input this value into the table below and calculate the r and p values for each machine. 5 pts, 1pt for correct tau, 0.5 pt for each correct p and r

Operation time = 103.68/7 = 14.81 hours. Accept rounding to 15.

	CVD	Fabrication	Singulation	Pick-and-place (multiple parallel)
Tau (hrs)	3	15	1	14.81

MTTF (hrs)	300	300	100	300
MTTR (hrs)	30	60	10	60
p tau/MTTF	3/300 = 0.01	15/300 = 0.05	1/100 = 0.01	14.81/300 = 0.049
r tau/MTTR	3/30 = 0.1	15/60 = 0.25	1/10 = 0.1	14.71/60 = 0.247

c) Using the long line MATLAB code to determine the production rate and optimal buffer size to maximize profit. **Paste screenshots of your MATLAB input and output, wherever appropriate.**

i) Using the values you calculated for the table in 4biii and the long line code, determine the **production rate (in displays/hour, not per cycle) of the system with no buffers**. 2 pts, 1 pt for inputting the correct values into the script. 1 pt for relating prodrate to P.

```
% Input parameters:
% Change the values for k, r, p, and N
% Click "Run Script" to calculate prodrate and nbar
k = 4;
r = [0.1 0.25 0.1 0.247];
p = [0.01 0.05 0.01 0.049];
N = [4 4 4];

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

▶ Run Script

Output

```
prodrate =

    0.6880    0.6880    0.6880


nbar =

    2.9140    1.8550    1.7723
```

Prodrate = 0.688 can be considered as the equivalent efficiency of the whole system. Therefore, the production rate of the system is:

$$P = \frac{e}{\tau_{max}} = \frac{0.688}{15} = 0.0459\ displays/hour$$

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 = 5000;    % Assume revenue of $5,000 per display
```

```
c = [12 8 12];       % 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 Save Reset MATLAB Documentation Open Item in MATLAB Online

```
% Input parameters:
% Change the values for k, r, p, and N
% Click "Run Script" to calculate prodrate and nbar
k = 0;
r = 0;
p = 0;
N = 0;

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

%Calculate hypothetical profit
pCoeff = 5000;    % Assume revenue of $5,000 per display
c = [12 8 12];      % Inventory holding cost per cycle
revenue = pCoeff*prodrate(1);
C_array = c.*nbar;
C_total = sum(C_array);
profit = revenue - C_total
```

Run Script

ii) Suppose you can add an **infinite buffer** to only one location (i.e. between machines 1-2, 2-3, or 3-4). By inspecting the process metrics of the production line from P4biii and the holding cost from the code provided above, determine the optimal location to place the buffer. 2 pts, 1 pt for recognizing balance, 1 pt for recognizing the cost difference.

By inspection:
From inspecting the table in P4biii, we can predict that the optimal buffer placement is between **machines 2 and 3** (between fabrication and singulation) to balance the production rate before and after the buffer. In addition, the additional code provided above indicates that the inventory holding cost is also the lowest at that location. Therefore, we can choose that as our optimal buffer placement and use the code to maximize profit.

By MATLAB code:
Using the matlab code, the highest prodrate was obtained when placing infinite buffer at 2-3, but the highest profit was obtained when placing infinite buffer at 3-4. This is because placing the infinite buffer at 3-4 results in much lower average inventory size (nbar), and the cost is based on nbar, instead of N. Accept answer between **machines 3 and 4**

iii) Determine the **optimal (finite) buffer size** at the same location you determined above to maximize the profit. State the **buffer size, average inventory, and profit.** 2 pts

You may need to do some trial and error; but based on the parameters you have previously calculated, a buffer size of 26-33 results in a profit > $3,600. Among these numbers, the buffer sizes of **29 and 30 both result in the highest profit of $3,601.6 per display.** Average inventory is shown in the screenshot results below: 13.47

```
% Input parameters:
% Change the values for k, r, p, and N
% Click "Run Script" to calculate prodrate and nbar
k = 4;
r = [0.1 0.25 0.1 0.247];
p = [0.01 0.05 0.01 0.049];
N = [4 29 4];

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

%Calculate hypothetical profit
pCoeff = 5000;    % Assume revenue of $5,000 per display
c = [12 8 12];      % Inventory holding cost per cycle
revenue = pCoeff*prodrate(1);
C_array = c.*nbar;
C_total = sum(C_array);
profit = revenue - C_total

```

▶ Run Script

Output

```
prodrate =

    0.7540    0.7540    0.7540


nbar =

    2.7437   13.4669    2.3017


profit =

   3.6016e+03
```

If the student chose **buffer in between 3-4** based on the last question, then the optimal profit is obtained for **N=31~33 and profit of ~$3,538.9.** Give full points for this answer.

```
% Input parameters:
% Change the values for k, r, p, and N
% Click "Run Script" to calculate prodrate and nbar
k = 4;
r = [0.1 0.25 0.1 0.24686];
p = [0.01 0.05 0.01 0.04937];
N = [4 4 32];

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

%Calculate hypothetical profit
pCoeff = 5000;     % Assume revenue of $5,000 per display
c = [12 8 12];       % Inventory holding cost per cycle
revenue = pCoeff*prodrate(1);
C_array = c.*nbar;
C_total = sum(C_array);
profit = revenue - C_total
```

Output

```
prodrate =

    0.7343    0.7343    0.7343


nbar =

    2.7810    1.7647    7.4342


profit =

   3.5389e+03
```

As we can see here, in case of finite buffer optimization, placing the buffer in 2-3 still produces the higher profit due to higher prodrate and lower unit cost. Intuition trumps over brute force coding.

Bonus Problems - Limitations and alternatives of pick-and-place (5 points)

a) A high-end pick-and-place machine has a placement accuracy of around +/- 5 micrometers. How does this accuracy compare to the minimum resolvable feature of the lithography process? 2 pts, 1 pt for bringing up rayleigh's criterion, 1 pt for recognizing the magnitude of difference in resolution between the 2 processes.

According to the Rayleigh criterion, the minimum resolvable feature is

$$x = k\frac{\lambda}{NA}$$

With k < 1 and NA ~ 1, the minimum resolvable feature is on the same order of magnitude of the light's wavelength. For visible light, this is already on the order of 100s of nanometers, and with EUV, this goes down to 10s of nanometers. We can see that the resolution afforded by lithography is a few orders of magnitude finer than that of the pick-and-place process.

b) To address the limitations of pick-and-place, there has been a push for "monolithic integration" of microLED pixels wherein wafers of different materials are transferred onto the same substrates and the microLEDs are fabricated layer by layer and aligned using lithography. Read: https://www.nature.com/articles/s41586-022-05612-1. **Discuss the advantages and disadvantages** of monolithic integration vs pick-and-place in terms of **throughput, performance, and yield**. 3 pts, 1 pt for discussing each metric

Throughput: as shown in Problem 4, the pick-and-place process has very limited throughput due to the time it takes to assemble each individual die. Monolithic integration and lithography, by comparison, is a much more parallel wherein an entire layer of pixel can be processed.

Performance: as discussed in part a of this question, lithography has a much finer resolution limit than pick-and-place allowing for high DPI displays

Yield: The monolithic integration process may have lower yield because requires several repetitions of transfer and fabrication. It is also more difficult to characterize the pixels in each layer and produce large format displays.