2026 METIIB Paper 1 Cribs

Question 1:

a)

i) Housing: toughness for drops, good surface finish/gloss, dimensional stability.
Mouthpiece: Biocompatibility (oral/mucosal contact), non-toxic, non-irritant, non-sensitising, minimal taste/odour; Mechanical robustness, biting, repeated use; Sterilisation/disinfection stability; Chemical and moisture resistance, stable in saliva.

(ii) Moulding quality risks and their mitigations. Any three of these possible options

- Sink marks/voids: Maintain uniform wall thickness; use ribs correctly (thin ribs), optimise packing/holding pressure and time; select gate location to maintain pack; consider gas assist only if appropriate.
- Warpage/dimensional drift: Balanced filling; symmetric cooling; control mould temperature; consider conformal cooling inserts; avoid sharp transitions; manage fibre orientation if reinforced grades used.
- Weld lines/weak points: Gate strategy to move welds away from high-stress regions; raise melt temperature and mould temperature within spec; use flow leaders; consider vibration welding/ultrasonic weld strategy if joining components.
- Flow marks/jetting/burn: Optimise injection speed profile; venting; avoid overly restrictive gates; ensure correct barrel temperatures.
- Stress cracking/chemical attack: Avoid aggressive cleaners if possible; select polymer and additives accordingly; minimise residual stress via processing; post-mould anneal if necessary for PC parts.
- Part-to-part colour variation: Tight control of residence time, shear history, masterbatch/compound lot control; avoid uncontrolled regrind.

b)

i) Manufacturing route (one realistic pathway, they may offer others)

- Ceramic Injection Moulding of near-net insert geometry (including nozzle plate region where feasible).
- DE binding and sintering with controlled shrinkage (tooling compensation + tight feedstock control).
- Micro-feature creation/finishing: laser drilling/trepanning of 120–200 μm nozzles post-sinter (or green-state where appropriate), followed by cleaning/debris removal.
- Ultra-precision finishing of critical surfaces: lapping/polishing of nozzle plate to achieve Ra < 0.2 μm locally; edge conditioning/chamfer as required.
- Metrology and Quality Assurance: optical/SEM for nozzle geometry, confocal/white-light interferometry for Ra, CT sampling for internal defects/porosity.

ii) Key constraints/risks and mitigations (any three)

- Sinter shrinkage variability: Tight control of powder/binder feedstock; SPC on green density; sintering profile control; design compensation; sampling-based metrology.
- Chipping/brittleness during handling/assembly: Edge radii; protective packaging; assembly fixturing; consider tougher ceramic (e.g., zirconia) if needed.

- Laser-induced microcracks / recast layer: Short-pulse regimes, correct fluence; process development coupons; post-drill cleaning and inspection; reject criteria.
- Nozzle clogging or debris retention: Ultrasonic cleaning; cleanliness-controlled assembly; design for purge; in-line flow test.
- Metrology throughput at 2M/year: Use in-line functional flow/leak tests for 100% screening; apply sampling-based high-resolution metrology for capability assurance.

c)

i) One example could be:

Hybrid architecture: a paced line with modular stations (or mini-cells) on a palletised conveyor, using recipe-driven “soft automation” for SKU flexibility (vision + robot/gantry pick-and-place) combined with dedicated tooling where it is clearly beneficial (e.g., leak test, sealing).

Key elements could be:

- Pallet with RFID/2D code for traceability and automatic station recipe selection.
- Quick-change feeders and poka-yoke interfaces for SKU-specific components (colour variants).
- In-line vision to confirm presence/orientation of insert, and gasket; reject early to protect OEE.
- Force-displacement monitoring for press-fit or closure operations (detects misalignment, missing parts, over-force).
- 100% leak test (pressure decay) and 100% functional test (sensor/firmware handshake) before pack-out.

ii) Possible key failure modes and how to detect could include:

- Missing or mis-seated flow insert: Detection: In-station vision; force signature; downstream flow test.
- Seal defect causing leakage / moisture ingress: Detection: 100% leak test; monitor weld/adhesive parameters; environmental stress screening sampling.
- Insert orientation error: Detection: Machine vision with fiducials/key features to confirm orientation and seating height; displacement/force signature monitoring during press-fit or placement; functional flow test (e.g., controlled airflow and measure pressure drop/flow rate).
- Micro-nozzle blockage or contamination introduced during assembly: Detection: Differential pressure / flow-through test; high-magnification vision inspection.

d) There are number of things to offer here.

- Cost driver: Lower tooling CAPEX but higher unit cost (materials + machine time + post-processing + QA).
- Lead-time/ramp-up: Fast iteration and late changes; useful for pilot and early market learning, but capacity scaling to 2M/year is challenging.
- Supply chain risk: Powder/filament qualification, machine fleet availability, and process drift; heavier QA and certification burden.

- Sustainability: Potential reduction in tooling waste and inventory; however, energy intensity and yield losses can be higher, and powder handling may increase operational controls.

For a stable, high-volume medical consumer product (2,000,000/year), use AM where it adds clear value (conformal-cooled mould inserts, fixtures, and pilot builds), then lock to injection moulding + robust automated assembly once the design and demand profile are known.

Question 2

(a) (i) It is anticipated that candidates will note that a secondary industry is focused on converting a range of commodity or primary products into final products for supply to consumers or industry for specific applications, whereas a primary industry is focused on bringing raw materials to a level of standardised commodify chemical or ingredient that can be provided to firms for further development into products.
In terms of common characteristics, candidates are anticipated to compare and contrast different common characteristics, such as levels and ease of innovation, flexibility/response time, demand variation, product throughput and unit, type of manufacturing plants (scale, continuous vs batch, quality measurements), lead times/responsiveness, product variety offered, etc.
A basic, acceptable answer will explain one term correctly and give 2-3 characteristics briefly for each case. A good answer will give a correct definition for both terms and 4-5 characteristics and communicate them clearly. A strong answer will give 6 or more characteristics and describe them very clearly. A strong answer will also note that this firm is a secondary industry because it is using the raw materials to produce a final product to supply to industry for a specific application.
(a) (ii) A basic answer would note briefly 4 steps. A good answer would describe 4 steps to a very good level of detail. A strong answer would describe 5+ steps with a very good level of detail. Candidates are anticipated to discuss the specification of the project, an initial update to the existing flow diagrams with new flow diagrams, describing what will need to be transported, from where/to where etc. Then there will be material and energy balances to ensure the volumetric flow and amount of heating are taken into account and the scale is known. This will be moved into a more detailed creation of a design flow-sheet. Then there will be a detailed Hazard Identification. Hazard and Operability studies are covered within the module and it is anticipated this will be drawn upon, although other aspects of safety are also acceptable. This will all enable a cost estimation prior to progressing.
(a) (iii) A basic answer would not the importance of measuring fluid properties through industrial flow tests and more quantitative rheology. A good answer would describe what rheology testing is doing in a bit more detail, applying a shear stress to understand the influence on the viscosity. At least one specific test will be described clearly. A strong answer will note that these are likely non-Newtonian, shear-thinning fluids, and link back to the importance of understanding this to enable mixing. It is anticipated that candidates will discuss tests to measure the yield point, to help understand how to make the material flow; to quantify thixotropy; understand the change in viscosity or non-Newtonian behaviour with temperature; and (in terms of the pot life), the change in rheology over time, and how long does it take for the material to become unworkable.
(a) (iv) A basic answer will focus on either 2-3 more chemical tests or performance tests, a good answer will have a mix of 3-4 chemical and performance tests. A strong answer will note 4+ tests, have a mix of chemical and performance tests, and describe them clearly. For example, candidates are anticipated to refer to DSC to look at the behaviour of the material after it is formed, to check the glass transition temperature, melting, or curing completeness. TGA may be employed to check for contamination. Typical performance tests include lap shear strength to look at cohesive and adhesive failure, tensile strength (how much it can stretch before breaking), peel strength, which links to dynamic conditions.
(b) (i) It is anticipated that candidates will discuss in a basic answer the very harsh conditions that a wafer and its environment experiences during manufacturing. This will include extremely harsh chemicals (plasma etching, chemical vapour deposition), fluctuating temperatures (and up

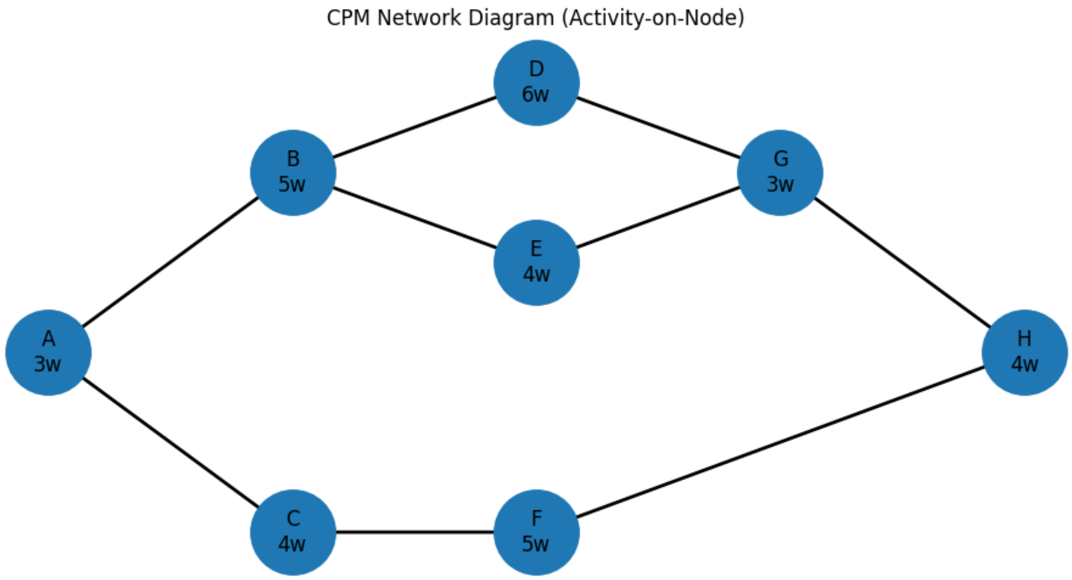
to around 1500 deg. C). It is anticipated that a good answer will expand to include aspects of electrical insulation, purity and dimensional stability. A strong answer will relate these aspects to wafer handling with a good level of detail.

(b) (ii) A basic answer will summarise very briefly the 4 key steps of material preparation, forming, firing and finishing. However a good answer would go into more detail about how the materials are prepared, the key components, and some of the challenges faced. It would also note a few different method of forming and what are the key differences, including considering aspects of green machining. The same is true of firing, as there are a few different options depending on properties, purity required. The finishing options would also be described in terms of laser machining, grinding, a range of surface treatments, etc. And quality control would also be acceptable if clear and examples given. A strong answer would give a clear, detailed answer to each aspect.

Question 3

(a)

Based on the precedence relationships, the project can be graphically represented by the network diagram below:



The earliest/latest start/finish times for the activities are as follows:

Activity	Duration	ES	EF	LS	LF	Slack
A	3	0	3	0	3	0
B	5	3	8	3	8	0
C	4	3	7	8	12	5
D	6	8	14	8	14	0
E	4	8	12	10	14	2
F	5	7	12	12	17	5
G	3	14	17	14	17	0
H	4	17	21	17	21	0

The critical path is therefore A-B-D-G-H (activities with zero slack).

The project duration is 3+5+6+3+4 = 21 weeks.

The planned project can be represented as a Gantt chart as shown below (critical path activities shown in dark grey):

By the end of week 12, if all the activities were started as early as they could have been, the planned status would have been:

- Activities A, B, C, E, F completed
- Activity D in progress – 4 weeks of 6

Budgeted cost of work scheduled (BCWS) = (30+75+60+60+75+90*4/6)*1000 = £**360k**

At the end of week 12, the following information is available:

- Activities A, B and C are complete.
- Activity D has not yet started.
- Activity E is 50% complete.
- Activity F is 30% complete.
- Activities G and H have not yet started.
- The actual cost incurred to date is £255,000.

Budgeted cost of work performed (BCWP) = (30+75+60+60*0.5+75*0.3)*1000 = £**217.5k**

Actual cost of work performed (ACWP)= £255k (given)

Schedule variance = BCWS-BCWP = (360-217.5)*1000 = £**142.5k**
Cost variance = ACWP-BCWP = (255-217.5)*1000 = £**37.5k**

The project is substantially behind schedule, which had planned for E and F to be finished and D well underway, but D has not started and both E and F are incomplete. The project is also over budget at this point, i.e. it has spent more than the value of the work earned.

(b)

Remaining activities and schedule: D, E (50%), F(70%), G, H

The overall activity schedule assuming all the activities start as soon as possible is shown in the table below (resource requirements shown):

Without any resource constraints, the project could have still been completed by the contractual deadline. However, as can be seen in the table, this schedule would require 8 people in weeks 13 and 14, which is not possible. In order to satisfy the resource constraints, activity D therefore cannot be started until activities E and F are finished. So the earliest that D can start is week 15. Hence the revised schedule is as follows (as can be seen, no other resource conflicts arise):

Clearly, the project will be 2 weeks late. In addition, Activity E is now in the critical path.

(c) (i)
Penalty: £40k per week late beyond 25 weeks.
From part (c), projected finish = week 27, i.e. 2 weeks late.
Penalty without crashing: 2* 40 = £80k

Crashing options:

Activity	**Maximum reduction (weeks)**	**Additional cost (£'000 per week)**
D	2	25
E	1	50
F	2	20
G	1	30
H	2	35

The critical path going forward is E-D-G-H. Therefore, crashing F does not reduce overall completion time (unless it becomes critical).
Current lateness: 2 weeks. To eliminate penalty entirely, need to reduce project by 2 weeks.
Cheapest crash cost activity is D. If we crash D by 2 weeks:
D becomes 4 weeks (instead of 6): weeks 15–18.

The revised schedule is as follows:

This allows the project to be completed on time without any penalty. You would not think of crashing any more activities since it will only add to the cost without any immediate financial benefit in terms of penalty avoidance.

[Note to examiner: Good candidates will note that activity F, although has the least crash cost, is not on the critical path, and therefore should be ignored. Poor candidates may choose to crash that activity (without any benefits).]

(ii) Overall cost calculation:
At the end of week 12, the cost incurred = £255k
Assume remaining work (apart from crashing increments) proceeds at planned cost rates:
Remaining budgeted work (from week 13 onwards):

- D: £90k (none done)
- E: £30k (half of 60 remaining)
- F: £52.5k (70% of 75 remaining)
- G: £45k
- H: £80k

Total remaining = 90+30+52.5+45+80 = £297.5k

Projected total without crashing/penalty = 255 + 297.5 = £552.5k
Including the penalty, total cost = £602.5k

(iii)

1. Schedule risk and lack of slack

- After crashing D, the project finishes exactly at week 25.
- Any small delay in the critical path activities would immediately cause lateness.
- Crashing further activities can create protective buffer even without penalty reduction.

2. Current critical path
- Activity E, which is already late is on the critical path. Also, D had to be delayed due to resource constraints. This raises some risk.

3. Uncertainty in activity duration
- The crashing analysis assumes deterministic durations.
- In reality, remaining work (especially G and H) is uncertain.
- Crashing reduces the exposure window to variability.

4. Resource stability and coordination
- Weeks 15–16 require 100% utilisation of all available staff.
- Any absence, rework, or inefficiency would immediately delay the project.
- Crashing F could reduce this peak loading.
- Long critical-path activities increase the risk of:
    - resource fatigue,
    - multitasking,
    - coordination failures.
- Shortening the remaining schedule can reduce organisational stress even if penalties are unchanged.

5. Managerial and strategic considerations
- Finishing early (or with buffer) improves:
    - confidence in delivery,
    - stakeholder trust,
    - ability to reallocate key staff earlier.
- Early completion may allow earlier realisation of operational benefits from the improvement project.

6. Consistency with EVA signals
- The project was already behind schedule at week 12.
- Even after recovery, management may adopt a conservative posture to prevent further slippage.

[Note to examiner: The final part is the key differentiator, with excellent responses including a wide range of reasons, with a good discussion]

Question 4

(a) Briefly describe how K-Nearest Neighbours (KNN) predicts the class label for a new data point.

[10%]

Answer:

KNN predicts a class by

1. computing distances from the new point to all training points such as Euclidean distance.
2. Selecting the K nearest neighbours (the K training points with the smallest distances).
3. Performing a vote on the neighbours's labels: the class that appears most among those K neighbours becomes the predicted class for the new point. For example, if among the 5 nearest neighbours there are 3 blue squares and 2 red triangles, the new point is predicted as blue squares by majority vote.

(b) Briefly discuss how an "optimal" value of *K* can be chosen in KNN?

[10%]

There is no predefined statistical method that always gives the best K. Instead, we choose a range of K values, train and evaluate KNN for each K, then select the K that gives the highest performance based on the evaluation on test or validation data.

(c) A company wants to classify whether a high-speed milling machine is likely to Fail or Not Fail. The company develops a binary classifier which is evaluated on a test set using a confusion matrix.

(i) Describe the performance metrics that can be obtained from a confusion matrix.

[15%]

Based on the confusion-matrix used for evaluation,

1. Accuracy that measures how often the classifier is correct is defined as:

$$Accuracy = \frac{number\ of\ correct\ predictions}{total\ number\ of\ predictions}$$

2. Recall (for the positive class, such as "Failure") that measures how many actual positives were correctly found is defined as:

$$Recall = \frac{correctly\ identified\ positive\ samples}{all\ actual\ positive\ samples}$$

3. Precision that measures how many predicted positives are truly positive is defined as:

$$Precision = \frac{samples\ predicted\ as\ positive\ that\ are\ actually\ positive}{all\ samples\ predicted\ as\ positive}$$

(ii) Briefly discuss the Precision-Recall trade-off in the context of predictive maintenance.

[15%]

Students will discuss the need to catch failures (high Recall) but also avoid too many false alarms (maintain Precision) and how this can be optimised with regards to cost functions. Excellent answers will also mention data imbalance.

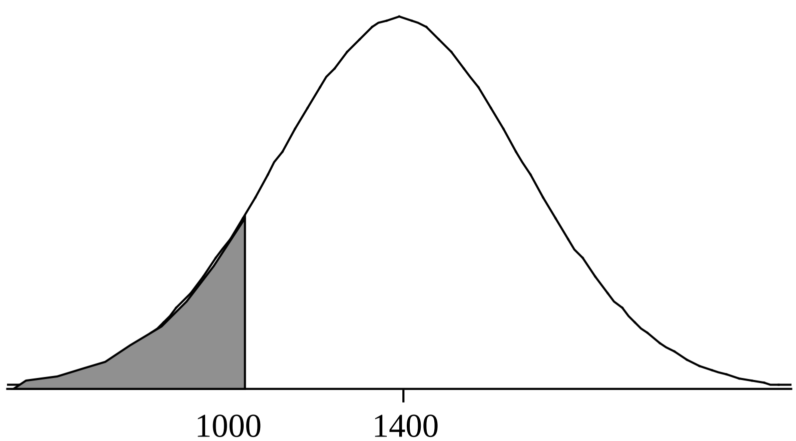
(d) The life of a certain type of electric light bulb is assumed to be normally distributed with a mean of 1400 hours and a standard deviation of 300 hours. The characteristics of the standard Gaussian distribution can be found in the Maths databook, page 30.

(i) If the manufacturer guarantees a life of 1000 hours, what percentage of bulbs can he expect to have returned?

[10%]

The normal distribution curve for this case is shown below.

Life~N(1400,300)



The number of standard deviations between 1000 and 1400 is

$$z = \frac{1000 - 1400}{300} = -1.33$$

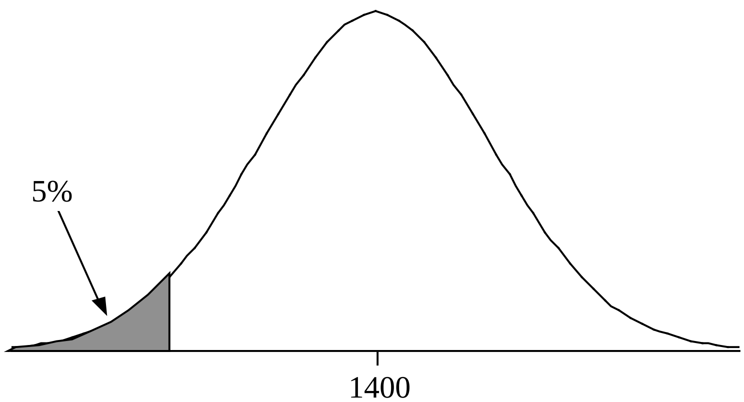
The negative z-value indicates that the point is to the left of the mean.
Referring to the table of tail areas of the normal distribution, we see that under the curve beyond 1.33 standard deviations from the mean is 0.0918. Thus the percentage of light bulbs that the manufacturer can expect to have returned is 9.18 per cent.

(ii) At what length of life should the guarantee be set in order for 95 per cent of bulbs to be found satisfactory?

[10%]

To answer this part of the question we need to use the normal distribution table in reverse since we know that a tail area of 1 - 0.95=0.05 is required, and we have to find the value that cuts off this area.

Life ~ N(1400,300)



The diagram for this part is shown above. Suppose the unknown guarantee figure is denoted by g. Looking up the area 0.05 in the normal distribution table, we estimate that the figure having area 0.05 beyond it is 1.645 standard deviations from the mean.

Using this estimate, we see that the guarantee needs to be set at
g = 1400-1.645*300 = 1400 - 493.5 = 906.5 hours.

(e)

(i) Explain what is archiving and its role in stochastic optimisation methods.

[10%]

An important element of all heuristic search methods is the way in which information about the search is recorded. Obviously one is interested in the best solution found to the optimisation problem under consideration (note that this is rarely the final solution visited in stochastic searches), but a stochastic optimisation method will inevitably have explored the search space quite widely and additional information about the problem being solved may well be of value. On the other hand, many thousands, perhaps millions, of solutions will have been examined and one would certainly not want to be presented with all that information. Some form of discrimination must therefore be applied when storing information to be presented at the end of the optimisation.

(ii) Describe two different types of archiving.

[20%]

Best L solutions

One obvious strategy is store the best *L* solutions located (their control variable, objective function and constraint values), where *L* may be of the order of 25. This is easily implemented. The one potential disadvantage is that the best 25 solutions may well be very similar and therefore this `archive' may not give very much information about the rest of the search space explored.

Best L dissimilar solutions

This disadvantage may be overcome by storing the best L solutions with a minimum level of dissimilarity. An obvious requirement is therefore a measure of dissimilarity between solutions. This is most readily defined in terms of the control variables. For instance, for continuous control variables, a simple measure of dissimilarity between two solutions x_A and x_B is:

$$D_{AB} = \sqrt{(x_A - x_B)^T (x_A - x_B)} \qquad (1)$$

i.e. the Euclidean distance between the solutions in control variable space. If the individual control variables vary over significantly different ranges (for instance, 0 m ≤ x_1 ≤ 10 m and 0 m ≤ x_2 ≤ 0.001 m, then it may be appropriate to rescale them so that within the optimisation routine they can vary over the same range, e.g. (0, 1) or (-1, 1).

In addition, one needs to define two dissimilarity thresholds D_{min} and D_{sim}, which are used as follows:

- Let the number of solutions in the archive be *l*, and let these be labelled x_K.

  Let x_J be a new solution, a candidate for archiving.

  Let x_E be the archived solution x_J most closely resembles, i.e. $D_{EJ} \le D_{KJ}\ \forall\ K = 1, \ldots, l$.

  Let x_G be the worst archived solution, i.e. $f(x_G) \ge f(x_k)\ \forall\ K = 1, \ldots, l$.
- If fewer than *L* solutions have been archived (i.e. the archive is not yet full), archive x_J if it is sufficiently dissimilar to all the solutions archived: If $l < L,$ archive x_J if $D_{KJ} > D_{min}\ \forall\ K = 1, \ldots, l$ (2)
- If the archive is full, archive x_J if it is sufficiently dissimilar to all the solutions archived and better than the worst of these:

  If $l = L,$ archive x_J if $D_{KJ} > D_{min}\ \forall\ K = 1, \ldots, L$ and $f(x_J) < f(x_G)$ (3)

  (In this case x_J replaces x_G in the archive.)
- If x_j is not sufficiently dissimilar to the archived solutions, archive it if it is the best solution found so far:

$$\text{If } D_{KJ} < D_{min} \text{ for some } K,\ \text{archive } x_J \text{ if } f(x_J) < f(x_K)\ \forall\ K = 1, \dots, l \qquad (4)$$

or, if it not the best solution found so far, archive it if it is sufficiently similar to and better than x_E:

$$\text{If } D_{KJ} < D_{min} \text{ for some } K,\ \text{archive } x_J \text{ if } f(x_J) < f(x_E) \text{ and } D_{EJ} < D_{sim} \qquad (5)$$

(In both cases x_J replaces x_E in the archive.)

Figures 1 and 2 show show examples of this logic in action for the simple case of an optimisation problem with just one control variable. Using this logic a helpful picture of the search space can be built up. Obviously appropriate values of the dissimilarity thresholds D_{min} and D_{sim} will be problem dependent. It is clear that $D_{sim} < D_{min}$ and indeed D_{sim} should probably be at least an order of magnitude smaller than D_{min}.

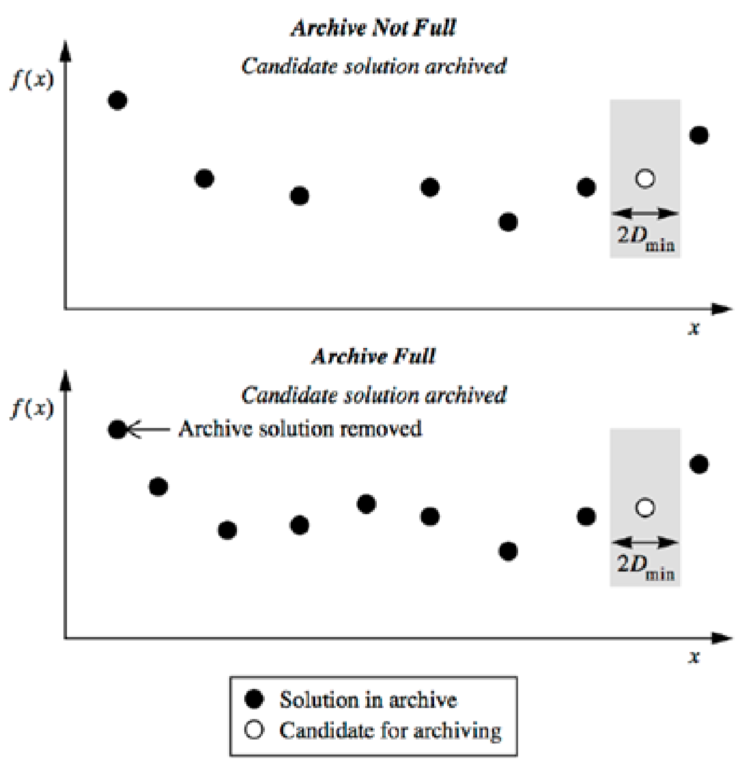


Figure 1: Dissimilarity archiving – D_{min} threshold met.

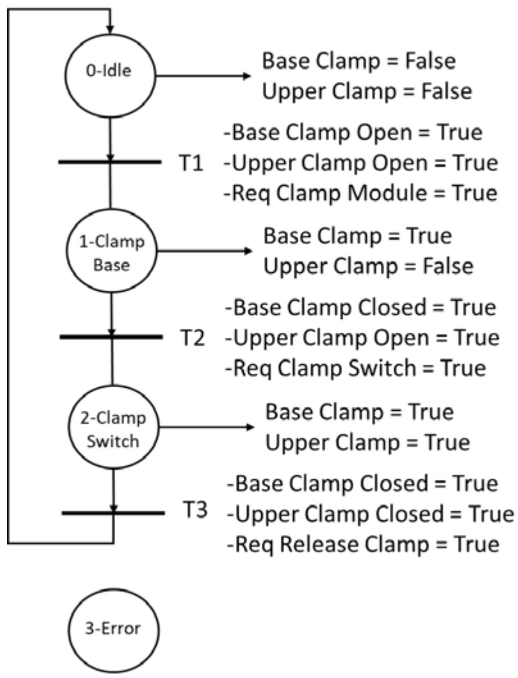
Question 5

ai) Robots have several coordinate systems or tool frames that can be used when implementing robot programmes. These frames are referenced to specific locations on the robot. World frame is referenced to the centre point of J1, Tool frame default is referenced to the centre point of the robot's face plate. Tool frame configured, moves the reference point to the tip of the end effector being used. By configuring and using the frames correctly, robot programmes can be developed quickly and made more flexible.
User frames are configured by the user and allow the robots world frame to be offset to a more useful location. In this application end effectors will be picked from tool holders. By setting up a user frame at a tool holder location, the robot's taught positions can be developed with reference to the holder's location. If for any reason the tool holder position needed to be altered, the user frame can also be updated and the existing robot's taught positions can be used.
In this application it is likely that the robot programmes for picking and placing of end effectors from tool holders will be the same. By setting up several user frames, one for each of the tool holder locations, the robot programme can be reused, selecting the appropriate user frame for the tool holder being accessed. When developing robot programmes that require positions to be offset by a user frame it is critical to use Position Registers (PR's). PR's are not specific to a single robot programme and can be referenced from multiple programmes. This provides an efficient way of reusing robot code when handling multiple fixtures and or component feeders.

User Frames -	**Mechanical / Location Benefits**
Accuracy	The user frame allows robot positions to be programmed with reference to a physical datum point (Reference point on fixture, feeder, etc.)
Change / Update to the physical environment.	User frames can be easily updated to new reference positions if physical components within the application need to be moved. This means that existing robot code needn't be changed.

User Frames -	**Code / Optimisation Benefits**
Reuse of robot code.	Robot code can be reused in a modular fashion to service multiple resources, switching in different user frames as required.

aii) Case statement is a coding instruction that can be used within structured text. It allows specific instructions to be executed depending on a specific case condition. Typically, the case condition reflects the current state of the system. The case state can be changed and or incremented depending on transition conditions, thus allowing a control sequence to be followed. Fig. 1 below shows a petri-net describing the operation of a fixture clamp. It also shows how the petri-net could be implemented using a case statement.




```
CASE State OF
0:  // Idle
     Base_Clamp := FALSE;
     Upper_Clamp := FALSE;
     // Transition Logic
     IF Base_Clamp_Open = TRUE AND
     Upper_Clamp_Open = TRUE THEN
     State:=1;
     END_IF;

1:  // Clamp Base
     Base_Clamp := TRUE;
     Upper_Clamp := FALSE;
     //Transition Logic
     IF Base_Clamp_Closed = TRUE AND
     Upper_Clamp_Open = TRUE THEN
     State :=2;
     END_IF;
.
. (This would be the code for the other states)
.
ELSE
      State :=3; // Error
END_CASE;
```

Fig. 1 Example showing the use of a Case Statement

When implementing a cell control, many case statements would be implemented. Typically, sub case statements would be developed to control each of the hardware functions, such as robots, fixtures, conveyors and vertical carousels. These sub case statements would allow the function of that hardware component to be requested from an overall cell controller. The overall cell controller would also be implemented using a case statement, but it would primarily be interacting with the other sub case statements.

Communication between cases statements can be carried out by monitoring the state of case statements or changing the state of a case statement, triggering them into action. In the Fig. 1 a case statement controlling the overall operation of the cell would interact with the fixture sub case statement. The current case state can be monitored to see if it's in a idle state and when required T1 can be triggered, requesting clamp module. Appropriate hand shaking needs to be implemented between the two case statements to ensure reliable operations.

aiii) The following table lists some examples of automation system characteristics that will address needs for flexibility and robustness.

Flexibility	**Robustness**
Use of Robots (Physical Flexibility)	Sensor Technology (Verify Operations)
Use of Tool Changes (Physical Flexibility)	Inspection Systems (Component tests)
Robot User Frames (Physical/System Flexibility)	Check/Safe Bits (Verify safe Operations)
RFID Technology (Tracking / Status Flexibility)	Unit/System Tests (Verify system development)
Modular Control Code (System Flexibility)	Follow ISO 95 / Verified Control Architectures
Open Control Architectures / Hardware	Verify suitability / failure rate of hardware

bi) The solution requires three sets of tasks to be achieved to successfully assemble a switch cluster module; a) Loading of the base assembly component (switch cluster module) and unloading of the finished assembly, b) OP1, assembly of switches into the switch cluster modules and c) OP2, assembly of buttons onto switches. Each of these tasks will require a robot to perform the relevant handling / assembly processes. (Three Robots are provisioned within the question) Due to the assembly task requiring a push fit action in the Z axis, it is proposed that SCARA robots are used.
The assembly processes for OP1 and OP2 will require a fixture. This will provide location accuracy when holding parts and rigidity during the assembly process. It is proposed that the same assembly fixture will be adequate for performing both OP1 and OP2.
To enable the handling of different parts during OP1 and OP2 assembly processes, the robots will be fitted with end of arm tool changers, allowing multiple end effectors to be used. In this solution each robot would need two specific end effectors and storage stations.
Parts are delivered into the cell in two formats; a) on kitting trays, singulated and correctly orientated for the assembly operation, b) within totes, randomly positioned and orientated. Kitting trays will be leveraged within the assembly process, using vertical carousels to store multiple trays, presenting a single tray as needed. Tote based components will be manually loaded into vibratory bowl feeders. The bowl feeders will store components and feed them correctly orientated for the assembly process. (Note it may be possible to use totes directly within the assembly process if the robots are fitted with vision systems and appropriate bin picking software tools.)
To move the assembly through the different operations it is proposed that a rotary turntable is used. Three stations would be positioned 120 Deg from each other. To ensure efficiency of the cell, it is critical that the robots are positioned to allow independent operations. Once operations have been completed in all three stations the turntable would be indexed by 120 Deg. Three fixtures would be located on the turntable at 120 Deg. Depending on performance requirements the number of fixtures could be increased in multiples of 3 and the index angle adjusted appropriately, ensuring that all fixtures are serviced. (Note stations could also be positioned along a linear track formation and further performance requirements would be required to determine the best solution.)

Component	**Sensors**	**Actuators**
Inbound Conveyor (PLC Control)	Kitting tray location sensors Docking station sensors	Stop dogs-Control tray motion Docking Station-Kitting trays
Bowl Feeders (PLC Control)	Part present at pick location Bowl empty sensor	
Vertical Carousel (PLC Control)	Tray at pick location Kitting tray location sensors	Control tray request (Level) Eject tray to pick location
Tool Changers (Robot Control)	End effector clamped End effector ID	Clamp / Release end effector
Tool Stations (Robot Control)	End effector present	

Robot End Effectors	Open / Closed	Clamp / Release components
Turntable Fixtures (PLC Control)	Part clamped / Fixture open	Clamp / Release components
Robot (PLC Control)	Integral Networking / Sensing / Actuation	
Turntable Servo Drive (PLC Control)	Integral Networking / Sensing / Actuation	

Fig 2 below shows the proposed floor layout for the system.

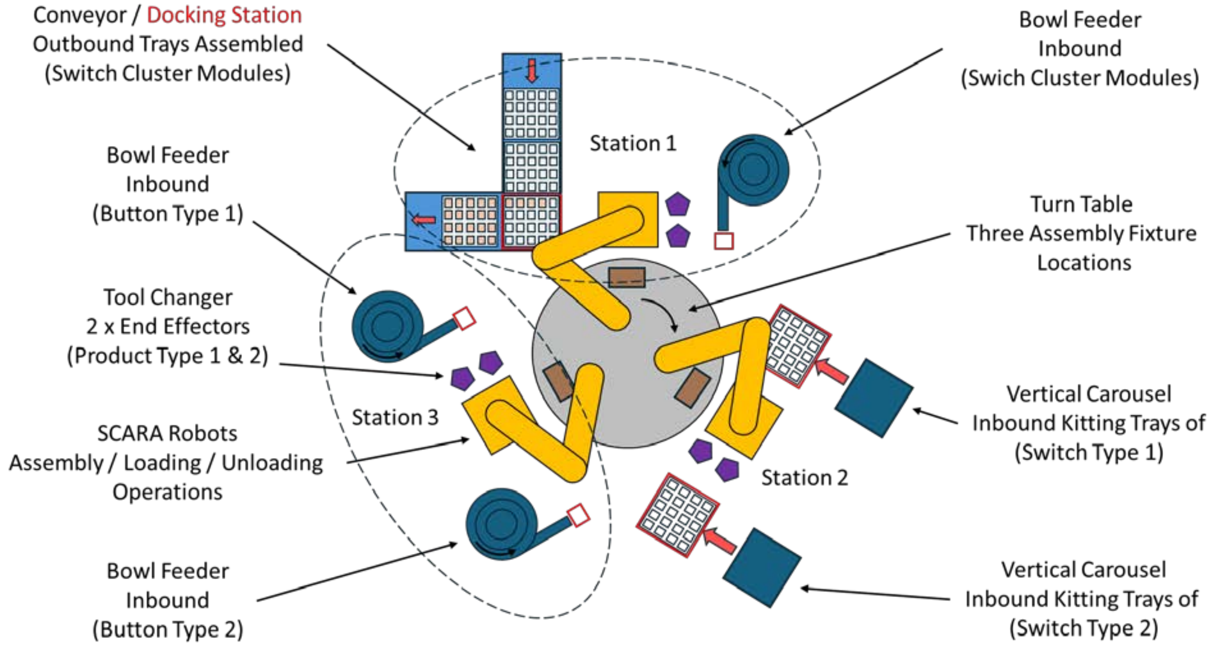


Fig. 2 Robotic Switch Cluster Assembly Cell

bii) The control architecture for the cell can be seen below in Fig. 3.

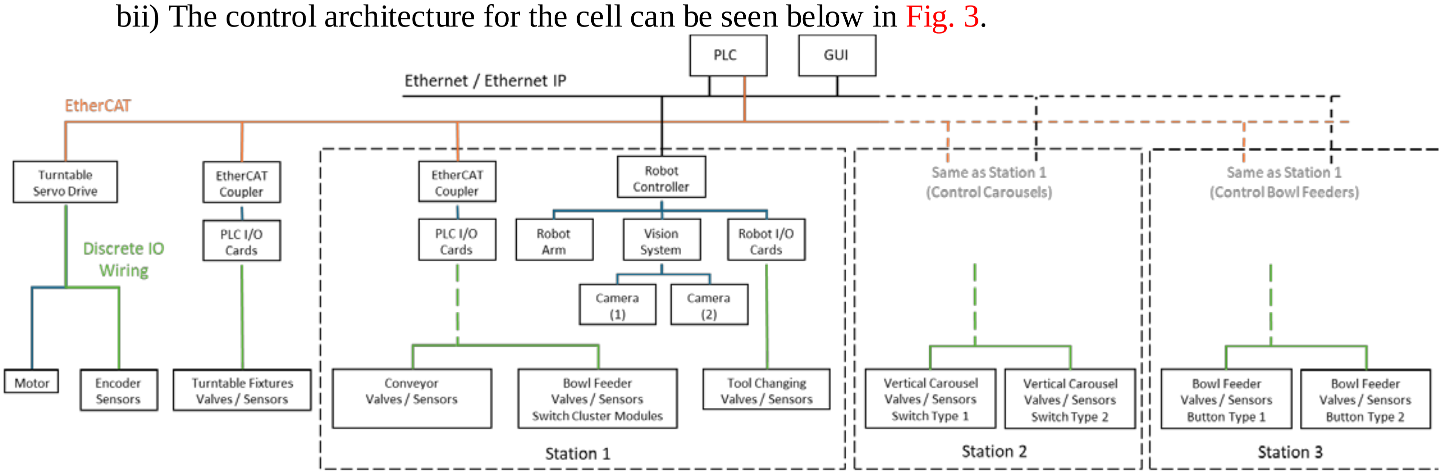


Fig. 3 Assembly Cell Control Architecture

In this application the PLC will provide the core sequencing of the cell operations, requesting robots to perform tasks, the turntable to rotate and fixtures to clamp and release parts. Sub functions, such as the operation of the vision system, tool changers and robot end effectors will be controlled via the robot controller.

Network / Interconnects	**Features**
Ethernet	Ethernet,(Office based network) Non-Deterministic and commonly used for the connecting of computing services. In this application if there was a requirement to integrate into an MES and or an SQL database, it would use this network.
EthernetIP	EthernetIP, (Automation network) Non-Deterministic but enhanced to provide communication services within controlled time limits. In this application the PLC and robots would communicate using this service. EthernetIP is a common protocol supported by higher level controllers. (Other Automation networks used in this type of application are ProfiNet / ProfiBus and more recently EtherCAT)
EtherCAT	EtherCAT (Automation network) Deterministic, provides robust communications over a dedicated network. In this application the PLC would communicate with IO Nodes and Servo drives using this protocol. (Vendor neutral technology with increased adoption in the automation sector.)
Dedicated Interconnects	These are specific to vendors and are used for interconnection of equipment. In this application the robot arm and the robot controllers, vision systems and the cameras etc. would use these specific connections.
Discrete IO Wiring	This is for the interconnection of low-level sensors and actuators to IO cards. IO link is a new communication technology that is being used in this area and allows for enhanced monitoring capabilities of sensors and actuators.

Question 6

a) An LCA evaluates the environmental impact across multiple impact categories which are relevant (human toxicity, eutrophication, abiotic resource depletion, and more). A system boundary must be determined and is used to define what factors should be included for a particular environmental analysis. It should separate those parts of the process which are being examined from those which are not part of the process being examined. The steps in an LCA are:

1. Compiling an inventory of relevant inputs and outputs of a system;
2. Evaluating the potential environmental impacts associated with those inputs and outputs;
3. Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study

Factors that could be considered: mining of the materials needed for the product, transportation of, component material production, product manufacturing processes, the weight and volume of the finished product for transportation purposes, the operational efficiency of the final product, how it affects the density with which the product can be packed for transport, and end-of-life disposal.

To perform an eco-audit we need to calculate the energy required, which is analogous to the carbon footprint, for every stage of the lifecycle of the product: material production, product manufacture, product use, and product disposal. Transport between all lifecycle stages is also calculated and can be included as a separate ‘stage’ of the lifecycle. Traditionally, the eco-audit methodology focuses on the phase with the largest energy usage in order to maximize impact reduction, however, the company should look at all phases to see where energy gains can be made.

The steps in an eco-audit are:
1. Compile a bill of materials for the product
2. Calculate energy used in the manufacturing operations for each component (all manufacturing steps)
3. Estimate the energy used in the ‘product use’ phase
4. Estimate the end-of-life energy use (recycling, re-use, disposal)
5. Estimate the energy used for transport between all stages (mode of transport, distances).

An LCA is more involved than an eco-audit. As mentioned, it assesses impact across many more categories than an eco-audit. It also only provides a final result, and does not break down the impact across different parts of the production process, which an eco-audit does.

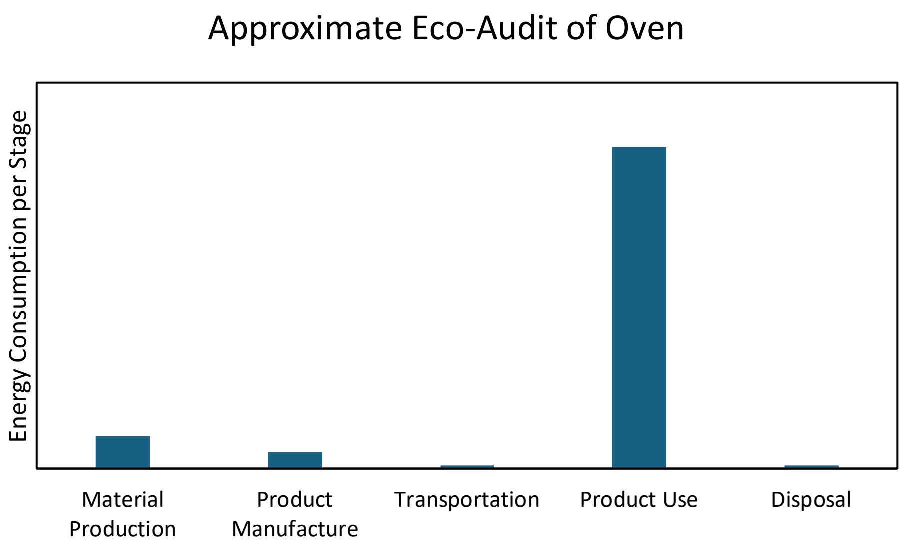
(b) Defining system boundaries for both LCA and Eco-Audit is crucial first step: a meaningful analysis of food packaging should include metrics of the efficiency of the packaging in performing its function of preserving and protecting the food. Factors directly relating to food include: food production, transport, storage (e.g. refrigeration), disposal. Factors relating to packaging are: material production, product manufacture, material disposal. Design factors are: material type required to fulfil function; thickness of material.
Eco-audit is in most ways the more appropriate tool, because the output is categorised into four lifecycle stages and the highest impact stage can be targeted for action to reduce impact. In the case of food, the eco-impact of food production is often orders of magnitude greater than the impact of packaging, so the greatest environmental benefit comes from reducing food wastage by

using the most efficient packaging. For LCA the answers may be more complex, and it's more difficult to separate out the impact of different stages.

b) This could be done in several ways which involve comparing different LCAs – by considering alternative materials for the food packaging, by considering changes to the existing packaging (for example thickness or design) to reduce the amount of material used, or by considering the specific part of the packaging that uses the most energy / could be most easily changed.

These would require doing the LCA several times, once as it currently is implemented, and once for each alternative. The most important assumption / piece of additional information needed is to include is the impact on the lifetime of the product. If it would shorten the lifetime of the food product, the LCA impact from this would need to be included.

c) The eco-audit takes this shape because during it's lifetime, an oven uses far more energy during operation than it does to manufacture due to heating up repeatedly for (presumably) years. The materials take some energy to make, and the oven needs to be manufactured, but this is not a particularly complicated process. To improve this, one could improve the insultation, so less energy is lost to the environment, reducing the energy demand to heat up.



d) The following factors should be considered: mining of the critical metal vs mining of the alternative, mining of other materials which may be necessary to use either in the product, component material production, product manufacturing processes which may be affected, the weight and volume of the finished product, the operational efficiency of the final product in case the alternative is not a direct replacement, how it affects the density with which the product can be packed for transport, and end-of-life disposal.

Answer standards:

<u>Basic answers</u>: Demonstrate understanding of the methods of lifecycle assessment and eco-audit and their environmental implications. May demonstrate lack of knowledge and understanding of some important factors. Examples may be inappropriate. The discussion may be superficial and inaccurate.
<u>Strong answers</u>: Good depth of knowledge and understanding. Will cover the key environmental aspects and provide adequate discussion with pertinent examples discussed with accuracy.
<u>Best answers</u>: Detailed descriptions and analysis. Demonstrate understanding of the more subtle tensions in the environmental assessments. Examples will draw on experience from many different parts of the course together with the student’s own observations. The discussion will be critical and insightful.