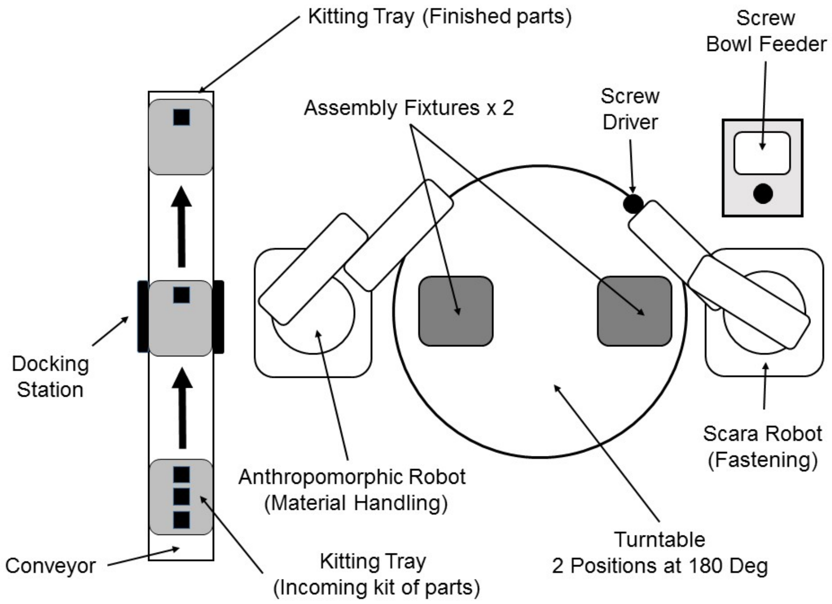
METIIB Paper 1 2015 Crib Final

Question 1 (AJT).

1a) The layout of the USB charger production system can be seen below.



The system makes use of equipment in the following way: (For Information not specific to question)

Equipment	Functionality
Conveyor	Transport of kitting trays in / out of the production facility. A docking station is used to locate a kitting tray so that the anthropomorphic robot can perform handling operations on parts.
Kitting Trays	The kitting trays are used to locate parts so that the anthropomorphic robot picks up parts for the assembly operation. The finished assembly would be placed back on the kitting tray to exit the production facility.
Anthropomorphic Robot	This robot has been chosen for the material handling operations as it is the most dexterous (5 Axis). It should be noted that this robot has limited load capabilities in the Z Axis. Care should be taken to consider if the screw fastening forces are higher than the snap fit assembly of the lid. (I am suggesting the screw fastening forces would be higher??) This robot would be fitted with vacuum sucker end-effector for picking up parts.
SCARA Robot	This robot has been chosen for the screw fastening operation. The robot movements required are suited to a 4 Axis robot and no wrist operations are required. SCARA type robots have good load capabilities in the Z plane, making it well suited to the screw fastening operation. This robot would be fitted with the screw driver.
Fixtures	Two fixtures would be fitted to the turntable so that material handling and screw fastening operations could be perform simultaneously. The fixtures hold parts so that assembly operations can be performed.
Screw Feeder	The screw feeder would be located near the SCARA robot. The screw feeder stores a number of screws and presents one screw at a time in an orientation for the screw driver to pick up prior to carrying out a fastening operation.
Turntable	The turn table is used to allow simultaneous operations of both the handling

	robot and the fastening robot. It rotates the fixtures into the workspace of the two robots.

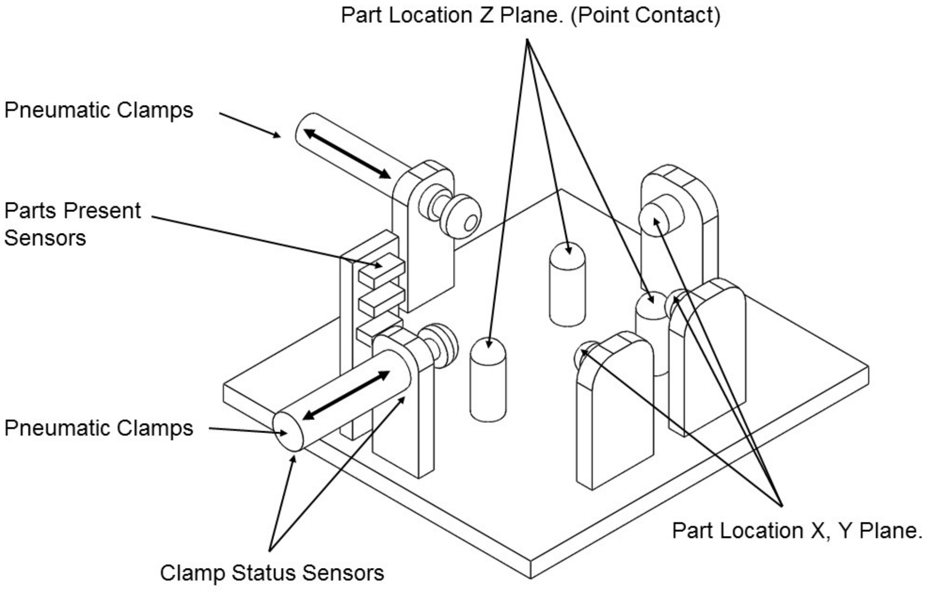
Discuss briefly considerations that you would make in using the turntable?

The turntable allows simultaneous operations to be performed by both robots, reducing the overall production cycle time. This also allows the robots to be dedicated to specific tasks and reduces the need for multi task end-effectors. To ensure that the turntable is providing an optimum solution it is important to balance the cycle times of each robot.

Operations that would be carried out simultaneously would be:

Anthropomorphic Robot (Part Handling)	SCARA Robot (Screw Fastening)
1. Place upper plastic moulding and Unload finished charger	1. Pickup and fasten screw 1
2. Load lower plastic moulding to fixture	2. Pickup and fasten screw 2
3. Load electronics module to fixture	3. Pickup and fasten screw 3
4. Pick up and hold upper plastic moulding	4. Pickup and fasten screw 4
	5. Pickup and fasten screw 5
	6. Pickup and fasten screw 6
ROTATE TURNTABLE	

(b) The design of the USB charger assembly fixture can be seen below.



The fixture has been designed to locate and hold the lower plastic moulding. Three point contacts are provided to locate the part in the Z plane. The orientation of these three points has been picked to match the fastening locations on the electronic module, thus providing optimum support during the fastening operation. Three point contacts are provided to locate the plastic moulding in the X, Y plane. The orientation of these three points has been picked to provide two points of contact on the longest dimension of the plastic moulding.

The fixture has an initial condition with all clamps retracted, providing the maximum space for parts to enter the fixture. The space provided is large enough to cater for part tolerance on the incoming kitting trays. Once the lower plastic moulding has been placed in the fixture the clamps are fired, pushing the plastic moulding against the fixed points in the X, Y plane. Sensors are triggered to show that both clamps are extended as expected and parts are present.

The electronics module and upper plastic moulding have no fixtures and rely on the accuracy and compliance of the assembly robot. Both of these assembly operations are aided due to the chamfer on the lower plastic moulding and the tapered snap fit locators on the upper plastic moulding.

Feature	Description of Functionality
Three point contact in the Z plane	To locate the components accurately in three dimensions it is important that kinematic principals are followed. This requires three points of contact in the Z axis. (Note that the three points of contact have been picked to match the fastening locations on the electronic module, thus providing optimum support during the fastening operation.)
Three point contact in the X, Y plane	To locate the components accurately in three dimensions it is important that kinematic principals are followed. This requires three points of contact in the X, Y axis. (Note that the three points of contact have been picked to provide two points of contact on the longest dimension of the plastic moulding.)
Pneumatic Clamps	To ensure that the components are located against the reference points and held in position two way pneumatic clams are used. These are positioned correctly to ensure clamping forces don’t skew the parts and cause deformations.
Pusher Pads	Pusher pads are present on the clamps to ensure that the product surface finish is not damaged.
Sensors	Three sensors are present at the side of the fixture to ensure that part present status can be determined (Lower moulding, Electronics and Upper moulding). Sensors are also incorporated in the pneumatic clamps. This allows the status of the two clamps to be determined.
Operation	It is important that when the clamps on the fixture are in the retract position enough clearance is available to ensure that the lower plastic moulding can be placed in the fixture while accounting for the tolerance of the robot and the part placement in the kitting trays.

(ii) The type and location of sensors required to ensure reliable operations of the fixture are discussed below.

The location of the assembly fixture sensors can be seen in the diagram above. It should be noted that the lower plastic moulding is made from plastic and so limits the choice of sensors to either being optical or capacitive proximity. I would recommend capacitive as they have less maintenance requirements e.g. cleaning of optics. Sensing the status of the pneumatic clamps can be done by a range of sensors, monitoring dogs on the shafts of pistons or by using specialised magnetic sensors that can be fitted onto the outside of the clamp cylinders. The electronics module and the upper plastic moulding could be detected with optical diffused sensors mounted on the periphery of the fixture. By testing the status of both the part presence sensors and the clamp status sensors it is possible to determine whether the lower plastic moulding is correctly positioned and clamped. (The Electronics Module and Upper Plastic Moulding may need additional assembly status information.)

Examiner's comments:

(a) More attention could have been paid to the location and operation of fixtures, and to explaining why a particular robot was used for each application.

(b) (i) The reason for the layout of the three points at the base of the fixture was often omitted, as was information on the location of the pistons.

(ii) More detail was generally needed on the location of the forward clamping pistons, particularly in the forward position.

2. (a) all AM processes involve converting a 3D CAD model of the object to be produced into a stack of 2D slices, which are then processed by one of the following methods described in the module (three only required)

Powder bed fusion: a thin even layer of powder is spread evenly onto a supporting plate, then a laser beam used to locally fuse particles together in regions where a solid product is desired. The powder layer is then moved downwards by a small distance and a new layer of powder is spread, followed again by local laser fusion. The sequence of powder deposition and laser fusion is repeated many times until the complete part has been created, embedded in a bed of unfused powder. The part is then removed from the bed and cleaned. Suitable for thermoplastic polymer or metal powders.

Vat photopolymerisation (stereolithography): a laser beam is scanned in a 2D pattern across the surface of a vat of liquid photopolymer to polymerise (and hence solidify) a 2D slice of the object. The object is then lowered slightly in the vat and the next layer is scanned. At the end of the process the solid 3D object is removed from the remaining liquid. Can only be used for photopolymer materials.

Directed energy deposition (e.g.LENS): uses a high-power laser (500W to 4kW) to fuse powdered metals into fully dense three-dimensional structures. The process is housed in a hermetically-sealed chamber which is purged with argon so that the oxygen and moisture levels stay below 10 parts per million. This keeps the part clean, preventing oxidation. The metal powder feedstock is delivered to the material deposition head by a powder-feed system which is able to precisely regulate mass flow. Once a single layer has been deposited, the material deposition head moves on to the next layer. By building up successive layers, the whole part is constructed. Applicable to metals.

Material extrusion (fuse deposition modelling FDM): molten thermoplastic is extruded continually through a nozzle which is moved in a series of 2D patterns to build up a 3D object. The polymer cools and solidifies shortly after leaving the nozzle. The object is moved slowly downwards as the build process continues so that the nozzle moves in a 2D plane representing each slice of the CAD model. To create overhangs a second 'support' material may be used, dispensed from a second nozzle, which is then removed (e.g. by dissolution) in a secondary processing step. Restricted to thermopolymers, although a similar extrusion process can also be used for clay/concrete/ceramic pastes.

Material jetting: 2D slices are created by inkjet printing of small droplets of photopolymer 'ink' (typically 20-50 μm diameter) which are then polymerised by exposure to UV light. By printing a sequence of 2D slices and moving the object downwards between slices, a 3D product is produced. Restricted to jettable photopolymers, although more than one material can be combined in a single product, for example to provide regions with different colours and/or mechanical properties. A similar process uses wax which is jetted in molten form and solidifies on impact; can be used to produce wax masters which are then used for investment (lost-wax) casting.

Binder jetting: inkjet printing is used to deposit a liquid binder material locally on to a layer of powder to define a 2D pattern corresponding to the 2D slice of the CAD model. The part is lowered slightly and a new thin layer of powder is deposited, and a new pattern of binder is printed. These processes are repeated sequentially until the complete part has been defined, when it is removed from the powder bed and cleaned of unbonded powder. The part may then be used as it is (for example, with ceramic particles, as a mould for metal casting) or further processed – e.g. by sintering (for metal or ceramic parts) or by infiltration by liquid metal into (higher melting point) metal powder. Applicable to metals or ceramics, or with a water-based binder to hydratable plaster materials.

Sheet lamination: 3D part is built up from a stack of 2D sheets, each cut to shape e.g. by CNC controlled blade or laser, then bonded together by adhesive bonding or ultrasonic welding. Limited use, limited to materials available in thin sheet form: paper, polymers, some metals.

(b) Good answers will consider the limitations of AM processes and compare them with more conventional processes. Points may include :

Speed: while low-volume AM production may be faster than conventional manufacturing (where set-up/tooling is considered), higher volumes are considerably slower. We will need a new generation of AM machines if we are to replace processes such as injection moulding and casting, because AM simply cannot do what the present technologies can do.

Affordability: the financial overheads for running machines and buying feedstock are potential barriers to the commercialisation of AM. Materials in powder form which are needed for many AM processes are intrinsically more expensive than wrought or cast materials for more conventional processes.

Reliability: it is difficult for AM technologies to compete with traditional techniques on reliability and reproducibility. For companies looking for a rejection rate of just a few parts per million, there is no way current technology can meet these demands

Education: the importance of educating everyone about AM, from the youngest school pupils to potential investors and leaders of industry, is essential if the technology is to be applied to better commercial success

Precision and surface finish: most AM processes leave a lot to be desired in terms of dimensional precision, reproducibility and surface finish, and the parts would require subsequent machining or other processing for many applications. AM cannot match conventional net-shape processes such as injection moulding and powder metallurgy in these respects.

Materials: many processes can handle only a narrow range of materials. Materials are often not optimised for AM processes. The range of alloys and polymers available for processing is limited. Polymers processed by AM are often more expensive, weaker and less durable than those processed for example by injection moulding, with limited colour choices. Photopolymers may contain residual chemicals that are hazardous for food contact or medical applications. Process conditions may not be well controlled, leading to unacceptable variability in performance of the final product.

Standards: we need a set of standards for processes and materials to provide much needed assurances to businesses and manufacturers that AM processes, materials and technologies are safe and reliable.

Intellectual property: the potential for users of AM to inadvertently infringe copyright is a serious concern

The suggestion that AM can affect 'the way we make almost everything' is surely an overstatement – current AM processes are severely limited in resolution (by laser beam spot size, powder particle size, inkjet drop size etc) to a few tens of μm which is far greater than the resolution needed for a large number of high-tech applications – e.g. AM cannot begin to match the resolutions needed for electronic devices. Even for many mechanical products (such as a simple bearing) we need a surface finish much better than 1 μm and material homogeneity on the ~μm level. AM lacks the capacity to handle multiple materials and interfaces between materials so that extensive post-processing and assembly will still be required. And all AM processes currently known are fundamentally slow, being dependent on layer-wise processing, so are intrinsically unsuited to volume production.

Examiner's comments: A popular question which was in general well addressed. In part 2(a), students mainly lost points by errors in the names of different additive manufacturing techniques and inaccuracies in the description of processes and material ranges. In part 2(b), most students discussed production volumes and cost, but very few discussed important considerations such as precision, surface finish and reliability. In general, the scores on part 2(a) were higher than part 2(b), which is probably logical since (a) asks for discussion of only 3 out of many additive manufacturing processes, while (b) requires a more exhaustive answer.

3. a) Nano materials can be broadly defined as those materials that have structured components with at least one dimension less than 100nm. Better students will differentiate their answer with extra detail. Nano materials can be described as having three basic classes:

Materials that have one dimension in the nanoscale (and are macroscoptic in the other two dimensions) are layers, such as graphene, thin films or surface coatings such as ALD TiO2.

Materials that are nanoscale in two dimensions (and macroscopic in one dimension) include Au metal nanowires and carbon nanotubes.

Materials that are nanoscale in three dimensions are nano particles, these include precipitates, colloidal suspensions (advanced paints) and quantum dots (light emitting semiconductor materials)

There are two principal factors cause the properties of nano-scale materials to exhibit remarkable properties that differ significantly from their macroscopic counterparts. These factors can change or enhance properties such as reactivity, mechanical characteristics, optical behaviour, thermal and electrical characteristics. These are:

Increased relative surface area. As a particle decreases in size, a greater proportion of atoms are found at the surface compared to those inside. Nanoparticles have a much greater surface area per unit mass compared with their larger counterparts. This effect greatly enhances chemical behaviour at the surface making nano particles of the same material much more reactive than the same mass of material made up of larger particles.

Quantum effects. Quantum effects start to dominate the properties of materials as size is reduced to the nanoscale. These can be seen in enhanced optical, magnetic and electrical performances. The effect is enhanced as the nano particle size reduces. Materials that exploit these effects include quantum dots (New TV displays), and quantum well lasers (tunable light sources) for optoelectronics.

b) The terms top-down and bottom-up manufacturing have gained significant meaning with the advent of nanotechnology.

Top-down fabrication is a subtractive process from bulk starting materials to make nanomaterials. Mechanical methods are the least expensive ways to produce nanomaterials in bulk. Ball milling is perhaps the simplest of them all. Ball milling produces nanomaterials by mechanical action in which kinetic energy from a grinding medium is transferred to a material undergoing reduction.

Thermal methods are plentiful. They are processes that provide heat to a material that is then used to thermally dissociate macro materials to form nanomaterials. High-energy methods such as those that require a large input of energy, such as: Arc discharge melting of bulk melting materials to produce nanopowders (used for silver nano inks and cu nano inks). Laser ablation of materials for nano particle production (quantum dots).

Lithographic methods are applied widely in the semiconductor industry. They are energy intensive and require expensive equipment and facilities.

Bottom-up fabrication is an additive process that starts with precursor atoms or molecules to make nanomaterials. Answers could include:

Chemical vapour deposition (CVD) is a gas-phase process by which reactive constituents react over a catalyst or pre-templated surface to form nanostructured materials. As an example, the economical synthesis of carbon nanotubes is by CVD. Precursors in the form of methane or acetylene or other carbon source gases are passed over Co, Fe or Ni catalyst. The precursors react with the catalyst particles to form nanotubes.

Atomic layer deposition is an industrial process that is capable of coating any material, regardless of size, with a monolayer or more of a thin film. A relatively pure bottom-up process starting with gas-phase constituents.

Molecular beam epitaxy and MOCVD are other industrialized processes that are considered to be bottom-up.

Liquid phase methods are also numerous. It is within the liquid phase that all of biological self-assembly and synthesis (e.g. colloidal synthesis, hydrothermal synthesis, or supra-molecular chemistry) occurs. Liquid phase methods are upscalable and low cost.

Electrodeposition and electroless deposition are very simple ways to make nanomaterials (dots, clusters, colloids, rods, wires, thin films).

Other bottom-up techniques include LBL, self-assembled monolayers, Langmuir-Blodgett deposition

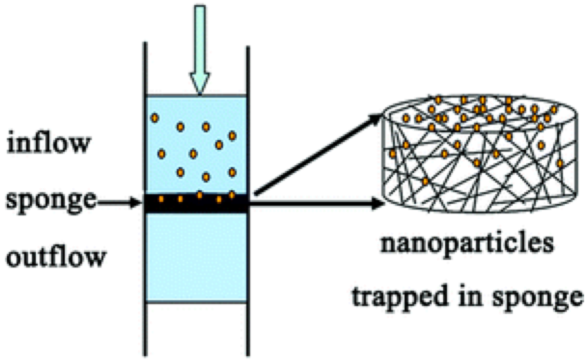
c) Answers to this question could be quite numerous depending on the background knowledge of each candidate. One particular example that was cited in lectures was the Use of CNTs.

In this case,

Choice of materials. Carbon nanotube (CNT) adsorption technology has the potential to support point of use based treatment approach for removal of bacterial pathogens, organic contaminants, and bacterial toxins from water systems. Unlike many microporous adsorbents, CNTs possess fibrous shape with high aspect ratio, large accessible external surface area, and well developed mesopores. These all contribute to the superior removal capacities of macromolecular biomolecules and microorganisms.

Materials production method; one of three main production methods should be discussed: Arc Discharge; Laser Ablation; and Chemical Vapour Deposition.

Basic system design; In this case an embodiment of the design could be as follows



Commercial issues that they may encounter using this new approach. Good answers will discuss the implications on their choice of production method. If they do not choose high volume production (CVD), the costs associated with implementing their approach will be too high and sales will be low. Other commercial issues concern health and safety of CNTs or their chosen material. Answers must consider how to control occupational exposure to manufactured nanomaterials in the workplace, but also how to limit exposure to the user during and after use. These considerations are an essential part of product development when applying nanoscale materials.

Examiner's comments: This probed the students' understanding of nanotechnology. While this material was covered in the lectures, there was only one attempt. The student that attempted this question answered it quite well.

4. (a) Servitisation is the innovation of organisation's capabilities and processes to better create mutual value through a shift from selling product to selling Product-Service Systems (PSS). A Product-Service System is an integrated product and service offering that delivers value in use. Firms use the following five routes to servitisation:

Add services by going downstream (vertical integration)

Could be termed integration oriented PSS – ownership of the tangible product is transferred to the customer, but the supplier seeks vertical integration, e.g. by moving into retail and distribution; financial services; consulting services; and transportation and trucking services
Effectively a product + a range of associated services
Relatively speaking: easy to implement and low risk
Example: Petrol stations, owned by oil companies

Add services to the product

Known as product oriented PSS – ownership of the tangible product is transferred to the customer, but additional services directly related to the product are provided, e.g. design and development services; installation and implementation services; maintenance and support services; consulting services; outsourcing and operating services; procurement services
Effectively a product + services integral to the product
Relatively speaking: easy to implement and low risk
Example: Apple, selling music and apps for electronic devices

Integrate services into the product

Could be termed service oriented PSS – ownership of tangible product is transferred to the customer, but additional services are offered as an integral part of the value offering
Effectively an integrated product-service system
Changes the nature of the business model, often shifts responsibility and risk
Reliant on technology so can require complex infrastructure
Example: Health Usage Monitoring Systems and Intelligent Vehicle Health Management

Shift focus to service (delivered through product)

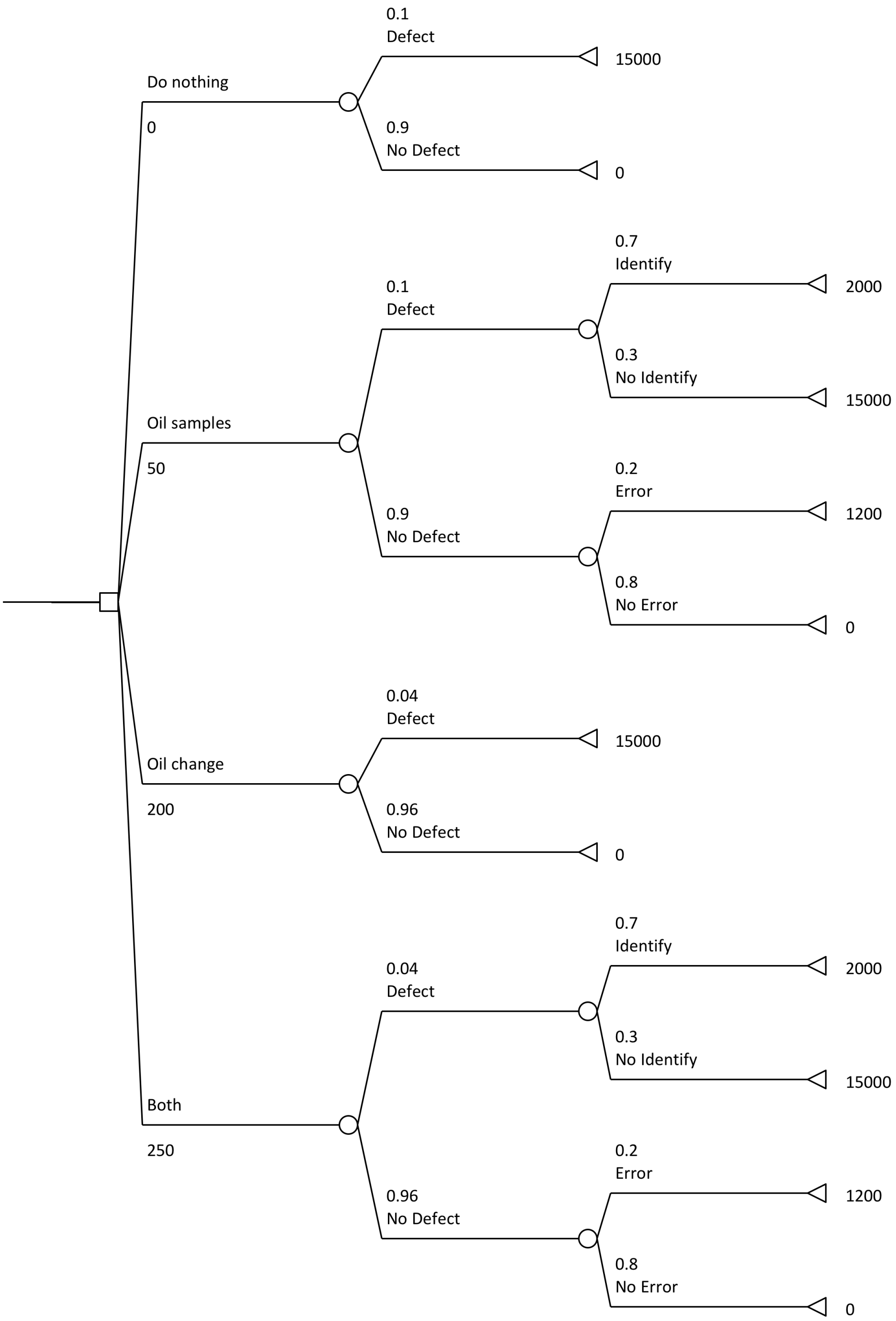
Known as use oriented PSS – ownership of the tangible product is retained by the service provider, who sells the functions of the product, via modified distribution and payment systems, such as sharing, pooling, and leasing.
Borrow/lease and return
Major challenge – change conceptions of ownership
Example: Zipcars, Netflix, Rolls Royce 'power by the hour'

Replace product with service

Known as result oriented PSS
The PSS replaces services for products
Example: voicemail service replacing answering machines

Examiner's Comments: Most identified the correct five different ways, with varying degrees of precision, and used appropriate examples. Less good was the discussion: rather few examined the advantages and challenges of these PSSs.

(b). The company must choose the strategy that delivers the lower expected cost. The most straightforward approach for this question is to use decision-tree analysis. The following decision-tree represents the choice of strategies and their expected outcomes.



Using the rollback process, the expected costs of each strategy can be computed.

The expected costs are:

Strategy 1:

15000×0.1 + 0×0.9 + 0 = £1500

Strategy 2:

(2000×0.7 + 15000×0.3)×0.1+(1200×0.2 + 0×0.8)×0.9 + 50 = £856

Strategy 3:

15000×0.04 + 0×0.96 + 200 = £800

Strategy 4:

(2000×0.7 + 15000×0.3)×0.04+(1200×0.2 + 0×0.8)×0.96 + 250 = £716.40

Hence the lowest expected cost strategy is to change engine oil at regular intervals and take oil samples regularly, performing maintenance repairs as indicated by the oil analysis (strategy 4).

Examiner's comments:

Marks were awarded for: using the correct rationale (lowest expected cost); clearly explaining the methodology (e.g., decision-tree analysis or otherwise); performing correct calculations for each strategy; selection of the correct strategy; discussion of the assumptions and limitations of this approach.

Most did the calculations correctly and identified the correct strategy. Explaining the rationale was less well done, and often omitted altogether.

Question 5 (AJT).

(a) Project milestones that should be considered in the development, integration and delivery of a typical automation project:
1 - Idea (Initial Requirement) [End Customer]
2 - Talk to various system providers [End Customer]
3 - Provide a Requirement Specification for Tender [End Customer]
4 - Basic Tests, Submit Functional Specification [Systems Integrator]
5 - Agreed Functional Specification (Performance Requirements) [All Parties]
6 - Prototype key technology components [Systems Integrator]
7 - Design System [Systems Integrator]
8 - Procure Components [Sub Vendors]
9 - Build Production System [Systems Integrator]
10 - Integrate System Components [Systems Integrator]
11 - Factory Acceptance Test (FAT) [All Parties]
12 - Site Acceptance Test (SAT) [All Parties]
13 - Final Performance Test [All Parties]

(b) The purpose of a functional specification is to:
Specify what the automation will achieve.
It will form the basis of the contract between the automation vendor and the customer, and will form the basis for the acceptance trials.
It will minimise specification creep.
Provide a base from which requested changes during the project can be identified and appropriately costed.
It forms the main means of communication between the customer and the vendor to minimise the chances of disappointment and / or nasty surprises
The main areas to be included in the functional specification:
What the system has to deliver (not on how this should be achieved).
Form, quality and method of delivery of incoming materials.
Form and method of delivery of finished products.
The functional specification will require further iteration with material suppliers and customers. The following additional areas should be covered:
The context within which the automation will operate, e.g. skill levels of operators, reliability of interfacing equipment outside the control of the vendor.

Cycle Time.
Some measure of availability, usually expressed as output over a specified period.
Form and extent of manual intervention.
Scheduled periods of operation and maintenance.
Levels of defects, and what to do when defects are detected.
Error detection and recovery, recoverable and non-recoverable errors. Form of error logging.
All the statements in the functional spec should be testable and so vague wording should be avoided. For example, "The system should operate reliably" is not acceptable, some measures of reliability should be provided.
(c) Different phases that should be included within a system's test plan are:

a) Unit Tests, b) System Tests

Unit tests are carried out on each component (Unit) of a production system. Typical components of a production system would be for example a Robot, Part Feeder or Conveyor Docking Station. Each component would be tested in isolation to ensure it works correctly and meets performance requirements specified within the functional specification. Typical Unit tests would include:
Test that hardware functionality meets performance specifications.
Operational status of hardware is reflected within the unit control system.
Error conditions are detected and captured correctly.
Unit control systems interfaces work correctly allowing systems integration to take place.
System tests are carried out on groups of production components once individual unit tests have been completed. A number of components are integrated together in these tests. The number of components is gradually increased as success criteria are meet. Typically these tests examine the way production components work with each other both at a hardware and systems level. Typical System tests would include:
Test hardware interfaces between production components.
Ensure correct software hand-shaking between component control system and overall production system.
Ensure that error recovery strategies for recoverable and non-recoverable errors work correctly.
These tests will go onto include specific production scenarios and provide the ground work for the Factory Acceptance Tests (FAT) and Site Acceptance Tests (SAT)
Examiner's comments:

(a) Generally fairly good responses.

(b) Often lack of attention to in/out material specifications and performance specifications.

(c) (i) Not well done: clear descriptions were generally not given.

(ii) Fairly good answers, but often without specifying that the Factory Acceptance Test should be followed by the Site Acceptance Test.

Q6 (a) (i) LCA (life cycle analysis) provides outputs under headings of resource consumption (including materials, energy, water), emissions (including various gases, particulates), and impact assessment (including ozone depletion, global warming, acidification, human toxicity). These different factors cannot readily be combined, so are usually left as separate datapoints.

There is currently no single method for conducting an LCA, but ISO14040 is an international standard which sets out a framework. It is a systematic way of analysing the impact of an activity or producing a product. It considers all phases of the lifecycle. It is useful for comparing the impacts of comparable activities (e.g. two ways of making a product). LCA is expensive, time-consuming, does have subjective elements, and is retrospective (normally too late to influence design). For the kettle, the outputs will include all those noted above (maybe in subcategories as well). It may be noted that most of the impact comes from the use phase.

Eco-audit provides a single measure of impact, which may be energy or CO2. This is generated under the headings of Material, Manufacture, Transport, Use and Disposal and usually presented as a bar chart. In addition a summary is generated showing detailed breakdown, life phase energies, life carbon footprints.

Eco-audit provides a quick and approximate measure of one aspect of environmental impact. Does not take full account of other eco factors which are included in full LCA. The following factors may be noted: gaseous emissions (e.g. SOX, NOX), particulates, ozone depletion potential, acidification potential, human toxicity potential. Water use is another big factor which may increasingly become a show-stopper. It identifies the dominant life phase so allowing a targeted approach to reducing environmental impact. It is done early enough in the design process to influence design. For the kettle, the use phase dominates, so the biggest improvement may be made by improving thermal insulation of the kettle.

Examiner's comments: Mixed answers, with a great deal of vagueness about LCA. Rather few identified that an eco-audit allows the design to be influenced, which is one of its great attributes.

(ii) LCA: Define goal and scope of study. Define the functions of the product system, functional unit, boundaries and product system. Define methodology, assumptions and limitations. Perform inventory analysis. Assign environmental impacts of product system. Interpret results.

Eco-audit: User inputs include Bill of materials, shaping processes, transport needs, duty cycle. The Eco database is used to generate embodied energies, process energies, CO2 footprints, unit transport energies etc.

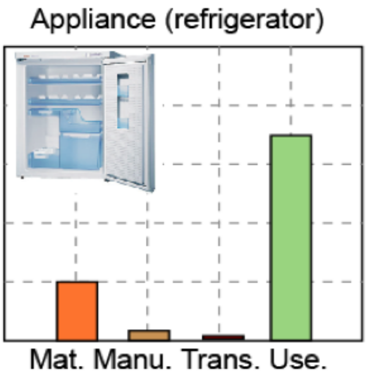
Examiner's comments: Generally well done.

(iii) The system boundary defines what is included in the LCA. Although the protocol is documented, it is subject to interpretation. For biodiesel, there will be variation in the extent to which growing of the crops is included, and how the agricultural systems are treated.

Allocation: Any process involves many systems, which are not independent. Allocation is the appropriate distribution of responsibility for resource consumption, emissions and wastes from processes.

Examiner's comments: Several defined system boundaries in general terms without specific mention of biodiesel. Rather few knew what is meant by Allocation; most just made something up.

(b) The eco-audit will generate a bar chart in which the dominant phase is the duty cycle, followed by the material. Increasing the operating efficiency of the fridge to reduce energy consumption will be the main recommendation. This will be achieved primarily by improving thermal insulation, though note that this will also increase the impact of the Materials phase. There may be scope within the design of the fridge for reducing the heat transfer when the fridge door is open – e.g. compartments in the fridge to retain the cold. Optimising the efficiency of the cooling mechanism is something else to be done – but there may not be much improvement possible there. There may be scope for encouraging good behaviour by incorporating alarms that sound if the fridge door is left open.



Even though the material impact is about one fifth of the operating impact, it could be worth looking at whether it can be reduced. Fridges contain mild steel, which is heavily recycled; this will have been accounted for in the material choice. Plastic parts will not be readily recyclable so will have some end-of-life impact. The main reduction in material impact will come from lightweighting. Transport is a small contributor to the total; fridges may well be manufactured at the other end of the world, but will be transported by sea which has a small unit energy burden. Manufacture is also a small contributor; many processes will be involved for the different fridge parts (e.g. wire drawing, sheet metal processes (cutting, bending), joining) but potential energy savings are unlikely to be dramatic for any of these.

Assumptions: May have to make educated guesses about transport and processes, location of material processing and manufacturing operations, and where the fridge will be used. These are important not only because of transport (and possible variations in plant efficiencies) but also because of the geographical variation of energy mix especially that used for electricity generation: e.g. hydro vs coal-fired generation. Materials may not be fully defined on BoM, so use appropriate substitutes. Some small parts may be ignored through lack of information: mention should be made of the likely impact of this.

Further assumptions include use phase (huge variability in user behaviour), product lifetime.

Examiner's comments: There was a tendency to produce a rag-bag of ways to reduce environmental impact, without much justification or rational discussion.

Although most people had mentioned that the eco-indicator approach is to choose the phase with the greatest impact and focus on reducing this to make the greatest gains, they didn't always put this into practice in prioritising recommendations.

Surprisingly, the most important factor (improving fridge insulation) was often not mentioned. Instead, people focused on improving thermodynamic processes and behavioural factors.

CYB