MANUFACTURING ENGINEERING TRIPOS PART IIB 2011/12 PAPER 1

Overall comment

The class average was slightly low this year essentially because of a single reason:- not paying attention to what the questions actually said. The details are given below in the comments on each question, but questions 1 and 5 – and most students did both these questions – had in essence a two-level request, along the lines of " explain to me how the thing works overall and also explain to me in detail what each element does". These are classic 'strategy and detail' questions and there is material of importance in both halves of the question. To fail to address one of the halves misses the point and leads to weak answers. Many students displayed this weakness to a noticeable degree in both these questions. It shows in the average marks for those two questions and they in turn influence the class average for the paper as a whole.

Q1

For each of the applications listed below, two or three possible manufacturing processes are proposed. In each case, briefly describe the processes, compare and contrast them, and discuss their suitability for the application.

(a) Sealing a container for an implanted heart pacemaker, made from thin titanium alloy sheet: adhesive bonding; friction stir welding; laser welding. [35%]

(b) Making a turbine disk for a jet engine from a nickel-based super alloy: hot forging; cold forging; casting. [35%]

(c) Making a container from a thermoplastic polymer for a high-value cosmetic product for retail sale: extrusion blow-moulding; injection stretch blow moulding. [30%]

Comment

The core request in this question was to describe several processes, compare and contrast them and discuss their suitability for a particular application. The question then gave three different examples. There were many excellent answers to part (a), many to part (b) and many to part (c), but rarely from the same student. And where a response to a section was weak it was that all three aspects of the core request were not answered for that section. There was one further error that numerous students made. Part (b) of the question was about making a turbine disk for a jet engine. It is true that Rolls Royce also make turbine blades, and these are cast in a very particular way using a pigtail lead into the casting chamber to grow a single crystal casting with a particular crystal structure orientation... but that has nothing to do with how they make turbine disks and is not an answer to this question.

Answer

(a) Adhesive bonding – uses 'engineering adhesive' often epoxy resin to bond surfaces by forming high-strength layer of cured polymer (thermoset) which adheres by mechanical and chemical mechanisms to the surfaces being joined. Importantly, the strength of the bond is much greater in shear than in tension and the joint should therefore be designed to exploit this – e.g. a lap joint rather than a butt joint between sheet materials. Can bond dissimilar materials easily.

Friction stir welding (FSW) –uses a rotating hard tool (cylindrical tip) between the two edges in a butt weld between metal plates. Rotation of the tool leads to mechanical disruption of surface oxide, some local heating by friction (but not enough to cause melting) and very heavy plastic deformation and mixing of the material close to the plate edges. Forms strong, autogenous bonds with no filler material.

Laser welding – uses very localised heat from laser source (several possible e.g. CO2 or fibre laser) to melt material in the joint region. Because the heat source is very intense (high local power density), there is rapid heating and cooling and the width of the melt zone and heat affected zone is small. Can be used as a high-precision process, without filler material.

Comparisons between processes: they differ in the use of filler material (adhesive yes, FSW and laser welding no); capacity for gap-filling (ditto); extent of heating (adhesive none, FSW some, laser weld to melting point); applicability to thin sheet (adhesive and laser weld yes, FSW no because of distortion caused by high local stresses during the process – although there is a micro-FSW process which may be better); applicability to dissimilar materials (adhesive yes, FSW and laser welding limited to similar alloys or in FSW alloys with quite similar mechanical properties); precision and need for subsequent clean-up or processing (adhesive and laser welding good, FSW poorer needing clean-up of surface burr).

To seal the external canister of a heart pacemaker we need a process that has very high integrity (quality of seal is vital for this application), can be applied to thin titanium alloy sheet, and is suitable for long-term implantation in the body. FSW as noted above would be unsuitable for thin sheet (although it can be used for Ti alloy plates) as it would probably cause too much distortion. There is a micro-FSW process which may be worth exploring, but whether it would be applicable depends on the geometry of the joint line and whether the forces which would be applied during the process are acceptable for the product – it is still in the development stage. FSW causes surface burr formation which may not be acceptable for an implanted component. Adhesive bonding would require a lap joint, and importantly would introduce additional materials into the component: epoxy resin and hardener. There are very stringent requirements for implanted materials and this would pose problems – they may well not be bio-compatible (indeed are very unlikely to be). Furthermore, epoxy resins can degrade with prolonged exposure to moisture and this aspect also raises doubts about adhesive bonding. Laser welding introduces no new materials, is capable of producing precise, thin bonds with minimal distortion and high strength, and would be the method of choice for this application.

(b) Hot forging and cold forging differ in the temperature of the workpiece, but are otherwise similar processes. For forming a disk they would involve a sequence of pressing stages for the metal billet between shaped dies, to achieve the desired final shape. The final stage might be closed-die forging (in which the die cavities match the final shape of the disk and the two dies come into contact at the end of the forging step), but the earlier steps would probably be open-die. The processes differ greatly in terms of the force needed (cold forging needing higher loads as the flow stress of the metal would be much higher), the extent of work-hardening (high for cold forging, nil for hot forging as dynamic recovery/recrystallisation would occur), the ductility of the metal (very high for hot forging, low for cold forging) and thus the number of forging steps needed (with intermediate anneals for cold forging). Hot forging can leads to surface oxidation which can be prevented or reduced by surface coating on part.

Casting would involve pouring molten alloy into a shaped mould (e.g. sand or ceramic mould for this size of component).

Forging processes give good control of final shape and microstructure, as grain size distribution and anisotropy can be predicted by modelling. The high plastic strains and recrystallisation in hot forging lead to homogenisation of the material, and elimination of any porosity which may remain after casting of the billet. In contrast, casting to final shape risks segregation (macro and micro) as well as porosity, slag inclusion and other defects. For this high-integrity application casting would be unsuitable, and cold forging would also be inapplicable as the forging load would be far too high (for this high strength material) and die wear/damage would be a problem, frequent intermediate anneals would be needed. Hot forging is the appropriate process.

(c) Extrusion blow moulding (EBM) – a thermoplastic tube is extruded from a shaped die to form a parison which is clamped into a hollow mould. The hot parison is then inflated by internal air pressure and expands to fill the mould. External features are defined by internal features in the mould.

Injection stretch blow moulding (ISBM) differs in that injection moulding is used to make a preform which is then heated and subjected to simultaneous axial stretching by an internal rod and expansion in the hoop direction by internal air pressure, inside a closed hollow mould. A single design of preform can be used for several different shapes of final product. Used only for a single polymer (PET).

Comparison of processes: EBM gives more consistent wall thickness, wider choice of polymers, cheaper tooling, simpler process, smaller economical batch size. ISBM gives more consistent thread detail (for screw closure), less mass variation, stronger bottle from stretching process, better concentricity/roundness, zero material wastage.

In principle both methods might be suitable – the choice will depend on factors such as the detailed design required, container shape, whether it includes extra features such as colour, surface texture, co-moulding, allowable cost, production volume, compatibility of polymer with contents etc. ISBM gives a gloss-surfaced PET container which is susceptible to surface scuffing damage – may be difficult to achieve the quality perception which is consistent with high value retail product. So on balance, EBM, possible with additional value-enhancing features, may be the process of choice.

Q2

The manufacture of an electro-mechanical consumer product, such as a DVD player, involves assembly processes for electronics components and mechanical components.

(a) Describe the range of electronics components, and related electronics component assembly processes, which may currently be used in building the electronics part of such a product. [50%]

(b) Discuss the range of mechanical assembly and automation methods that could apply over the lifecycle of such a product, and the factors that would determine the most appropriate choice of assembly method. [50%]

Comment

This question was answered well by most students. Part (a) of the question asks about electronics components and component assembly processes. Some students wasted time but did not lose any marks, by additionally describing how you make microchips from silicon... interesting, but not what the question asked about. The few weak answers were lacking in showing the detail in their answers that signifies good understanding of the electronic component assembly processes and then, quite separately in section (b) of the question, the mechanical assembly processes used in creating the finished product.

Answer

(a) Good answers will describe the categories of components that exist and may be used. This includes:

Active and passive components.

Active includes diodes, transistors, integrated circuits (ICs), for example microprocessors and applications specific ICs (Asics).

Passive includes resistors, capacitors, inductors, connectors.

Components may also take a variety of forms which affects how they are assembled in a circuit (usually onto a printed circuit board, pcb):

Through-hole components (assembled through holes in the pcb):
Axial – where the leads are in line with the component
Radial – where the leads are at right angles to the component

Surface mount devices (components), (SMDs), where the component has no leads and is mounted directly onto the underlying circuit. Better answers will mention the varying size of SMDs, and the trend to ever smaller size.

ICs may also take a wide variety of package forms, of varying size and means of mounting onto the circuit. They may be through-hole , but are more usually surface mounted. More knowledgeable students will give examples of the forms such as dual-in-line, flipchip, chip-on-board, ball grid array (BGA).

The other key component in the DVD player is the laser.

Assembly processes that could be used to build the circuits of these components are pick and place machines, either for SMDs, ICs, or through-hole connection. Manual methods may be used for difficult to handle, low volume items.

A key aspect of the assembly processes is the soldering methods used, and good answers will describe the range of these, linked to component types, and the steps within each process.

Hand-soldering for low volume, difficult to handle components, for example edge connectors.

Wave soldering – an automated process mainly for through hole components in pcbs. After fluxing, the pcb rides over a wave of molten solder which 'wicks' up each protruding lead, making a solder connection to the local track on the pcb.

Reflow soldering – used for SMDs, where solder paste is applied by screen printing to the points on the pcb where a component is to be placed. After all components are placed, the pcb is passed through a reflow oven, which heats the solder paste up to the reflow temperature of the solder, thus forming joints.

Given the typical volumes made of the DVD product, the processes are likely to be predominantly automated SMD placement and reflow soldering.

(b) This part of the question concerns mechanical assembly rather than electronics assembly, so the discussion of component placement techniques should not be repeated.

The range of mechanical and automation options for automating assembly covers:

- mechanised methods, in which machines help people to do the job
- hard automation, in which machines do the same job every cycle
- flexible automation, in which robots and other software-driven machines do the job, which can be different each cycle

Solely manual methods may also be considered, as these may be used for very low volume products.

Mechanised methods make use of tools (eg powered screwdrivers), simple parts handling and orientation devices, but the human operator is at the centre of the assembly activity.

The important issue raised by the question and which candidates should consider, is the lifecycle of the product. This refers to the fact that any product is introduced to the market, may succeed and ramp up in volume, but will eventually decline in volume as it ages, becomes less attractive to buyers, and is possibly replaced by a new model or simply discontinued. There are also pre-market aspects to the lifecycle, when development and prototyping are under way. The means of mechanical assembly needs to be appropriate to the point in the lifecycle at which it is used – which means that they may need to change over the lifecycle.

A combination of product and market attributes governs the way assembly is carried out. Candidates may refer to the 'Puttick Grid', which categorises products according to production and market certainty on one axis, and product complexity/variety on the other axis. The resulting four quadrants on this grid depict commodity products, consumer durables, jobbing/fashion products and capital equipment (super value goods). Each quadrant has its own distinctive characteristics in terms of manufacturing system requirements.
The DVD player was a consumer durable when first introduced, but with growth in volume and reduction of price in the market, has become a commodity.

Factors to take into account when choosing assembly method include: flexibility, reliability, quality, speed, capital investment, running costs, volume growth and lifecycle of the product, hazards (to assembly operators). Component and task variability are also important considerations. Automated systems have difficulty with high variability, whereas human operators are very flexible and adaptable, and may even enjoy such variety.

From these factors, students should also consider whether manual assembly, hard or soft (flexible) automation is appropriate. In this context the graph below (figure 1), presented during the teaching module, will be useful. It compares the fixed capacity of hard automation with a robot cell solution (soft automation) and manual assembly, through the product lifecycle.

Considerations for outsourcing assembly to low cost locations may also be discussed. Logistic and quality risks are important factors to be considered, and the possible cost of providing technical support to a sub-contract manufacturing company of less experience.

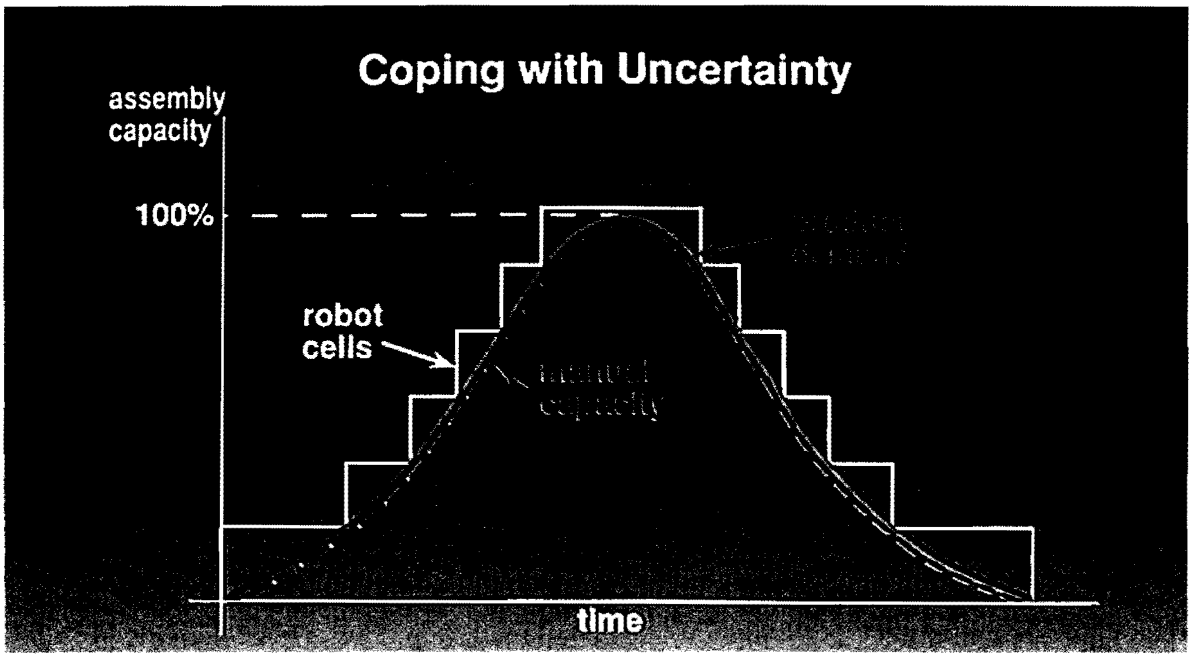


Figure 1: Capacity comparison of manual, robotic (flexible) and hard automation systems over the product lifecycle

Given the expected high volumes of a consumer electronics product such as the DVD player, the choice will be between hard automation (uneconomic at the low levels of utilisation characteristic of the beginning and end of the lifecycle) or more flexible automation which can track demand levels and be more easily redeployed to other products.

Q3

As the number of internal combustion engines rises steadily in the global economy, there is a compelling impetus to develop clean, efficient, and suitable vehicles for urban transportation. As a result, Hybrid Electric Vehicles (HEV) and Fully Electric Vehicles (FEV) are now joining the product portfolios of many of the world's leading automotive companies.

(a) Describe the basic architectures of both HEVs and FEVs. Discuss the advantages and disadvantages of each, and assess their environmental benefits. [40%]

(b) There are a number of rechargeable battery technologies that have been used or are likely to be used in the future for HEVs and FEVs. The lithium-ion cell has only recently begun to replace the lead-acid cell in transport applications. What are the environmental benefits to the customer in using lithium-ion cells compared to lead-acid cells? [40%]

(c) Given the need to provide safe electrical systems in HEVs and FEVs, explain why the electrical systems run at high voltages instead of low voltages. [5%]

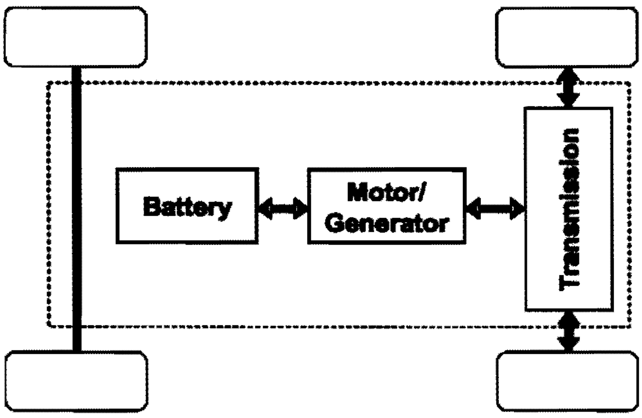
(d) Describe three safety concerns for passengers when using HEVs or FEVs. What measures could be taken to reduce the risks? [15%]

Comment

Only a few students answered this question but it was the best answered question on the paper, with students not only describing well the essential features of electric vehicles as discussed on the question, but giving balanced answers outlining the potential problems as well as potential advantages of these vehicles still being developed.

Answer

a) ***Fully Electric Vehicles (FEV)*** refer to vehicles propelled solely by electric motors. The source of power stems from the chemical energy stored in battery packs which can be recharged on the electricity grid. Based on the type of transmission; the use of a clutch, gearbox, differential, and fixed gearing; and the number of battery packs and motors, there are many variations on the FEV design. However, a basic FEV system should be presented as follows. Good answers will highlight the two way arrows indicating the direction of the flow of energy through regenerative breaking.



Advantages:

- Zero emissions at the point of use
- Low running costs
- Quiet operation
- More reliable (less moving parts)
- Low maintenance

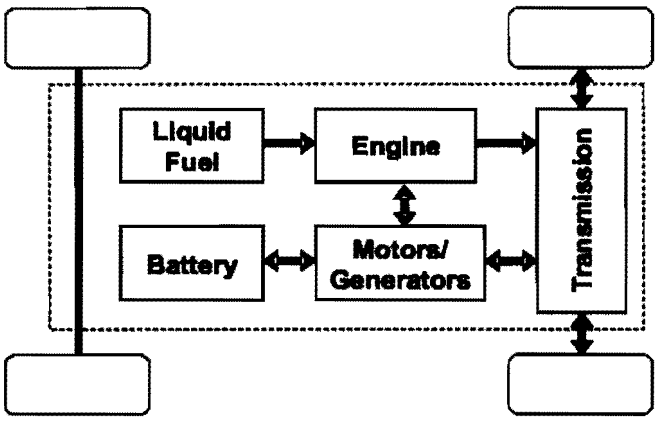
Disadvantages:

- High capital cost

- Small size
- Limited range
- Slow recharge rates and limited re-charging facilities

A ***Series-Parallel HEV*** has both Series and Parallel energy paths. As shown in figure below, a system of motors and/or generators that sometimes includes a gearing or power split device couples allows the engine to recharge the battery. Variations on this configuration can be very complex or simple, depending on the number of motors/generators and how they are used. These configurations can be classified as Complex hybrids (such as the Toyota Prius and Ford Escape Hybrids), Split-Parallel hybrids, or Power-Split hybrids.
Note: Good answers will detail the additional options offered by a HEV
The Parallel Hybrid can operate in the following five modes:

- Engine only traction
- Electric only traction
- Hybrid traction
- Regenerative Braking
- Battery charging from the engine



Advantages:

- Ability to run on charge depletion or Charge Sustaining mode
- Grid Connection capability
- Extended all electric range which can displace significant quantities of fuel
- Fuel consumption reduced over conventional vehicles
- GHG emissions are reduced (depending on the electricity generation mix)
- Wide driving performance

Disadvantages:

- High level of complexity
- Additional weight
- Higher initial costs
- Higher production and disposal emissions than conventional vehicles

The principle environmental advantage of FEVs is that they are the only commercially available zero-emission vehicles (ZEVs). Being zero-emission, EVs therefore provide local environmental benefits - including cleaner air and reduced noise in urban areas. Emissions are produced during the generation of electricity, the amount depending on the method of generation. When conventional power station emissions are taken into account, most impacts are still significantly reduced - for example the life cycle CO_2 for a mains-powered electric car is typically 40% less than for a petrol equivalent. Where pollutants are generated, these also tend to be emitted away from major urban areas. If renewable electricity is used, then all life cycle emissions are virtually zero. The same argument goes for HEVs, although the life cycle reduction in CO2 emissions will be some where in between ICEs and FEVs, depending on the size of the engine and the complexity of the HEV systems

b)

1) Charge time 10- 30 minutes 10% to 96% (>400 volts)
   Charge time 30 minutes for <150 volts but requires very large currents and special Battery Chargers.
2) No Daily/ Weekly Maintenance.
3) No Battery swapping.
4) Improved safety factor with no Battery Handling
5) Greater Usable Energy Capacity (80% to 85% vs 50 to 60% for PbA)
6) Greater Energy Efficiency e.g. Regenerative energy absorption (96% vs PbA 10 to 20%)
7) No Toxic gas generation during charging or Heavy Duty operation
8) No corrosive chemicals
9) Weight Reduction (Currently 1/3 of PbA)
10) Smaller Size (Typically ½ of PbA) allows for a Vehicle Platform design without a focus on battery access

c)

The choice of operating voltage is based on the power losses associated with the particular configuration and the need to minimize the heating (lifetime limitations) of the battery during normal operation, and the reduction in the size (diameter) of the electrical wiring loom.

For example to deliver a power of around 20kW (a moderate power level of an FEV motor), the power loss in the battery is determined by I^2R, where I is the current and R is the internal resistance of the battery. So for a power of 20kW:

At 50V and a very good battery with an internal resistance of 3mΩ, we have

Power loss = 400 A x 400A x 0.003 Ω = 480 W

At 500V and a very good battery with an internal resistance of 3mΩ, we have

Power loss = 40 A x 40A x 0.003 Ω = 4.8W

There are some moves towards developing mid-level voltage systems of around 120V, although these have yet to be taken up by manufacturers.

d) Discussion points could include:

Electric Shocks from the Cells

The battery pack in an FEV is electrically isolated from the chassis. Many of the electrical components, such as the speed controller and charger, will not function if they detect very lower currents to the chassis

The FEV also has various safety disconnects including a main contactor, a circuit breaker, and fusible links. All of these can be used to manually disarm the battery pack circuit, or they operate automatically in the case of tools dropped across battery terminals, collision damage, or some other situation that causes a surge of current.

Dangerous EM fields

EMF is commonly associated with AC devices than DC systems used in FEVs Measurements taken inside FEV while driving have found insignificant EMF readings. The only significant amounts of EMF can be found close to the charging circuit (which has AC input). Research on EMF within FEVs is still on-going, although manufacturers are currently designing EM shielding around the cabling and drive systems.

Battery Fires

FEV Battery systems are engineered to resist high external temperatures, and have internal circuit breakers to prevent shortages and rapid discharge between the cells.

Q4

(a) Discuss the key issues to consider when designing an asset information management solution. [40%]

(b) In the context of maintenance practices established at ExxonMobil, explain how "response maintenance" is effectively implemented. [60%]

Comment

This question relates to a particular part of the course in which some very detailed, world-leading industrial practice is shared by the industrial practitioners concerned. It is pleasing to see that most students were confident to answer this question and answer it well. The weaker answers were lacking in the understanding of the crucial details that make this approach to asset management and asset maintenance so distinctive and effective.

Answer

(a) The key issues that will drive the solution and the approach are:

- What does the client want to use the data for?
    - Collection of raw data does not in itself provide value - this information must be managed, combined & enriched using other data sources to develop real insights rather than raw data
- What types of assets, parameters & conditions does the client want to monitor?
- What existing information systems are in place?
    - This will drive the need for integration with existing solutions
- How ready is the client to use the information?
    - The client needs the business organisation and systems capability to make use of the data and insights
- Any solution needs to consider legacy technology, suppliers / partners
- Any solution will need to consider industry/sector standards, if any.

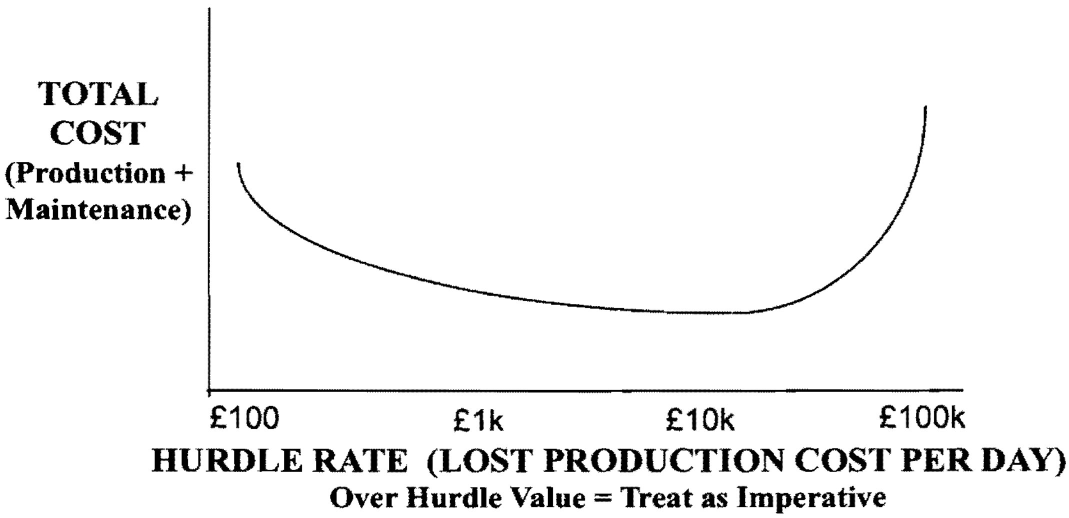
(b) There is a substantial amount of analysis done to identify different kinds of failure and the necessary equipment needed to respond to that failure, and fully prepared kits of tools, spares and so on are established and maintained so that whenever any failure occurs, the relevant kit if tools etc. is already prepared and available. There are also instructions as to how to do the necessary repairs.

An important element of "response" maintenance is in fact very detailed and thorough planning. Part of the planning is a categorisation of failures into those needing an imperative response, because of the high financial loss of downtime, and those where some delay can be afforded to enable a well organised repair to be carried out.

In a standard response, when an item fails, engineers go and establish the scope of the problem and needed response, and produce a scoping report, by mid-day on the day of the failure. They then schedule the repair for 5 days from the failure date, and order the necessary resources to do the repair. On the repair date the repair team execute the repair with no disruption. The plant is then handed back to operation.

An imperative response is still planned before execution begins. When an item fails, the work is scoped, the resources are ordered and the repair is planned, but an imperative response is allowed to override other work to draw people to complete it in faster than the 5 days of the planned response work.

ExxonMobil has established a plant-wide measure called "hurdle rate" used for categorising failures in terms of whether a "standard" or "imperative" response is required. The hurdle rate is the threshold cost that different failures will cause per day due to lost production, which is used to determine which failures are responded to as imperative. If a graph is plotted of total cost of "lost production costs plus maintenance costs of all failures" taken together, with the hurdle between standard and imperative responses set at different lost production cost levels, this will show as a graph of total cost set against the hurdle rate, assuming 5 days of delay in a standard response. The hurdle rate is set to give the minimum total cost.



Q5

As a production engineer, you have been asked to design an automated system that will perform the final assembly of an electronic consumer product. This process is currently carried out by manual labour and involves positioning a lid onto the base of the consumer product and then fastening it in place with three screws. A conveyor system and standardised kitting trays are used to transport the base of the consumer product and its associated lid into the assembly process. The assembled consumer product is transported out of the assembly process using the same kitting trays. Fig. 1 shows an exploded assembly drawing of the electronic consumer product.

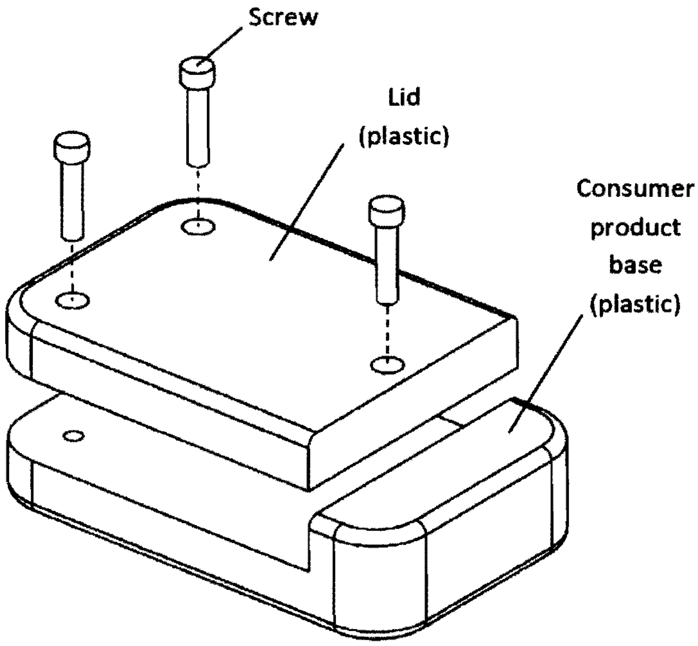


Fig 1. Exploded assembly drawing of the electronic consumer product.

A number of pieces of hardware have been made available to automate this task:
1 x (4 Axis Scara Robot)
1 x (5 Axis Anthropomorphic Robot)
1 x (Bowl Screw Feeder)
1 x (Rotary Turntable, with two operational positions at 180 Deg.)
1 x (Electric Screw Driver, with a vacuum system for picking up individual screws)

(a) Draw a floor layout of the new automated production system making use of the supplied hardware, with additional assembly fixtures and end effectors. The design should make use of the existing conveyor system and kitting trays for transporting parts in and out of the system. Describe the overall operation of the system, listing the specific features of the hardware components that make them suitable for task. [40%]

(b) Provide a detailed design of a fixture that can be used for the assembly / fastening operation of the consumer product. Describe the overall operation of the fixture, listing aspects of the mechanical design that enable it to work reliably. [40%]

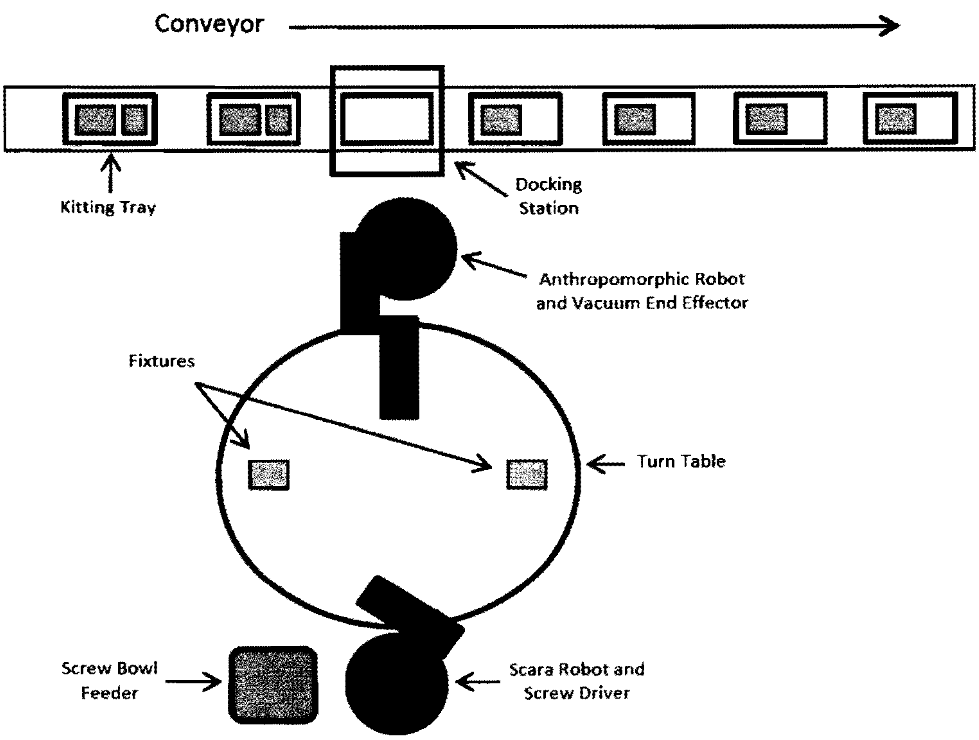
(c) Describe the type, location and functionality of sensors required to ensure the reliable operation of the fixture. [20%]

Comment

This question had the same characteristic shown in question 1, of requesting descriptions of overall processes and then a listing of the specific features of the elements that made it work reliably. This core question repeated through the three sections of the question. There were many excellent answers to parts (a), (b) and (c) but rarely from the same student, and this lack of consistency led to the low overall average for the question. And similarly to question 1, when a weak answer was given to one section of the question it tended to be along the lines of only answering one of the two core elements of the question. One student gained few marks for part (b) of the question by presenting an answer that was nothing to do with the design of a fixture for use in the assembly/fastening operation of the product.

Answer

a. The layout of the automated system for the electronic consumer product can be seen below.

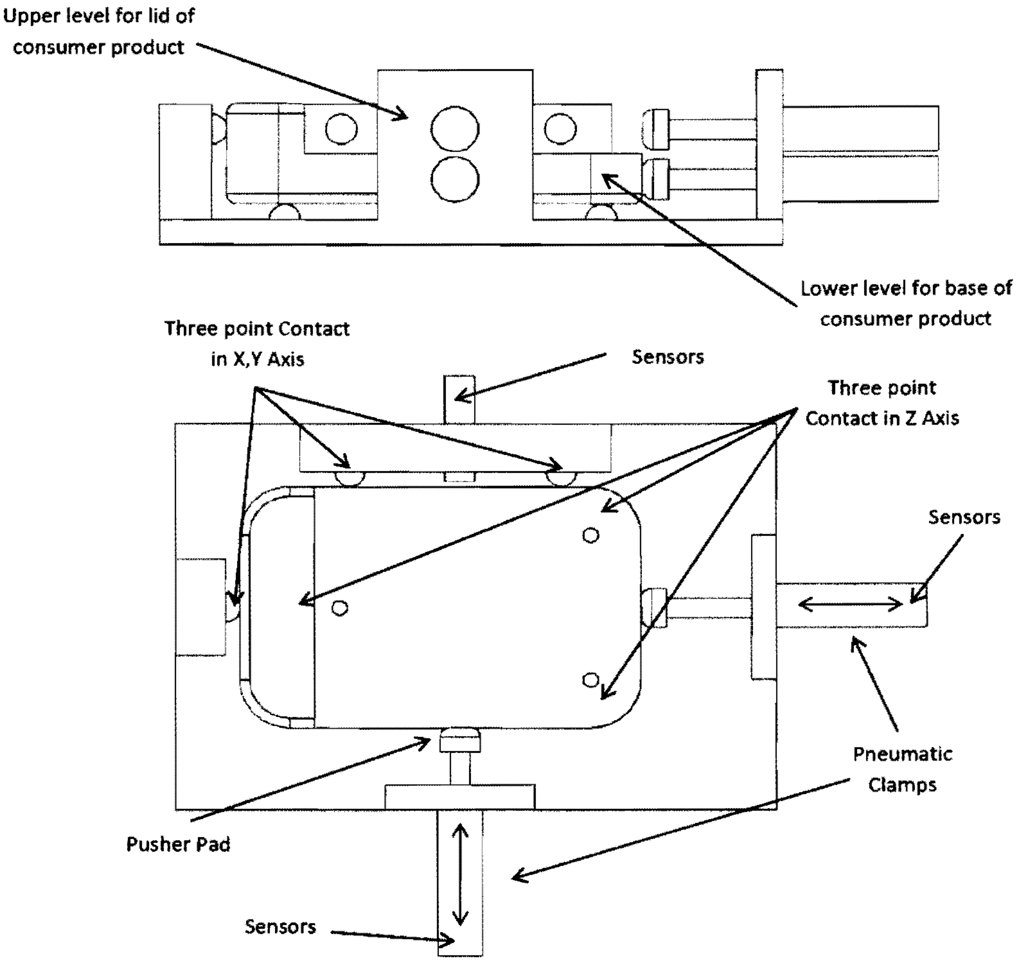


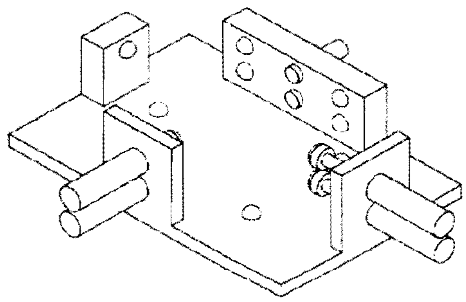
Components arrive at the conveyor docking station on kitting trays and are held until the Anthropomorphic Robot and an empty fixture become available. The base of the consumer product is loaded into the fixture by the Anthropomorphic Robot using a vacuum end effector. Once in place the lower half of the consumer product is clamped. The lid of the consumer is then moved into position and clamped in place. Once both the Anthropomorphic and Scara robot are inactive the turntable is rotated through 180 deg. The Scara robot then moves to a screw pick-up location at the bowl feeder, picking up a single screw with a vacuum fitting before moving to and performing the first of three fastening operations. This process is repeated a further two times for the remaining screws. The screw driver is fitted with appropriate sensors to ensure that screws have not been dropped or cross threaded during the process and have been torqued correctly. At the same time that the Scara robot is performing the fastening operation the anthropomorphic robot unloads any finished components from the opposite fixture on the turntable.

The following table lists the key features of the components used in the system.

Component	Features
Anthropomorphic Robot	The anthropomorphic robot is best suited for transporting parts between the kitting trays and the fixtures. This is due to its configuration and 5 axis of freedom, making it very dexterous. It should also be noted that it has limited load and stiffness capabilities in the z plane, making it less suitable for screw fastening operations.
Vacuum End Effector	The anthropomorphic robot is fitted with a vacuum end effector and suckers, enabling it to pick up the plastic components. The vacuum end effector is fitted with sensors to ensure its robust operation during the pick and place process.
Scara Robot	The Scara robot is best suited to perform the Screw Driver Operation. It will be required to manipulate the screw driver between the screw bowl feeder and fastening locations over the fixtures. The Scara robot configuration provides both high forces and stiffness in the Z axis.
Screw Driver	The Scara robot is fitted with a screw driver end effector. The Screw driver is fitted with sensing to ensure its robust operation.
Bowl Feeder	The screw bowl feeder is used to feed screws from a hopper to a pick-up location in the correct orientation. The screw feeder provides information about the presence of a screw at the pick-up location and warnings about low screw levels in the hopper.
Turntable	The turntable has been used to reduce the cycle time by allowing the simultaneous operations of both the Scara and Anthropomorphic Robot. The turntable enables both robots to access fixture locations.
Fixtures	The fixtures are used to locate and hold the parts of the electronic consumer product during the screw fastening

	operation. The fixtures are active devices fitted with clamps locking parts into known locations and are fitted with sensors to ensure robust operation. In this example two fixtures have been used.





b. The fixtures would be designed as shown below:

The fixture has an initial condition with all clamps retracted, providing maximum space for parts to enter the fixture. Once the base of the consumer product has been placed the two lower clamps are fired, pushing the base against the fixed stops. The lower sensor is triggered allowing operations to continue. The lid of the consumer product is then placed on top of the base. Once placed the upper clamps are fired, pushing the lid into position and triggering the upper sensor. With both parts being clamped in place the fastening operation is able to take place.

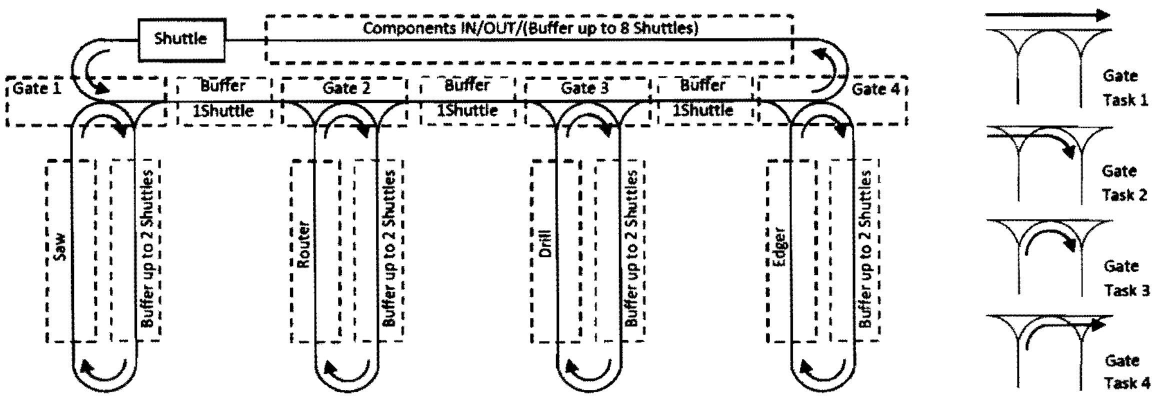
The following table lists the key features of the fixture that are important for its operation.

Feature	Description of Functionality
Three point contact in Z Axis	To locate the components accurately in three dimensions it is important that kinematic principles are followed. This requires three points of contact in the Z axis. (Note the three points of contact have been located close to the screw locations to ensure no movement during the fastening operation.)
Three point contact in X, Y Axis	To locate the components accurately in three dimensions it is important that kinematic principles are followed. This requires three points of contact in the X,Y axis.
Pneumatic Clamps	To ensure that the components are located against the reference points and held in position pneumatic clamps are used. These are positioned correctly to ensure clamping forces don't skew the parts or cause deformations.
Pusher Pads	Even though a single point of clamping is theoretically preferred, this can cause damage to the surface of the components so a pusher pad is used to spread the load.
Fixture Levels	The fixture is designed to account for the two levels of the component; the base and the lid are located and clamped separately.
Sensors	Sensing is critical to ensure correct operation of the fixture. Sensors have been positioned to register the presence of a correctly clamped component. Additional sensors can be added to the pneumatic pistons to register if they are in an extended or retracted position.
Operation	It is important that when the clamps on the fixture are in the retract position enough clearance is available to ensure that parts can be placed in the fixture while accounting for the tolerance of the robot and kitting trays.

c. The sensors are located as shown above in the fixture diagrams. It should be noted that the components are made from plastic and so limit 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 pistons can either be done by a range of sensors monitoring dogs on the shafts of the pistons or by using specialised magnetic sensors that can be clamped onto the outside of the clamp cylinders. By testing the status of both the part presence sensors and the status of the clamp sensors, it is possible to determine whether are part is correctly positioned and clamped. (Both clamps extended + both part presence sensors triggered)

Q6

A cabinet manufacturing company has developed an automated production system used to machine MDF panels. The panels can be machined to different sizes allowing a wide range of cabinets to be made. The system consists of a number of production resources that can be used to perform tasks such as sawing, routing, drilling and edging. Depending on the style and size of cabinet to be manufactured, these resources can be utilised in different sequences, following different specifications. A new flexible conveyor system has been installed to transport MDF panels through each of the production resources. It is similar to a mono rail, with gates that allow shuttles to be routed in different directions. The sub-loops enable shuttles to pass directly into the work area of the production resources, allowing machining operations to be performed directly on parts located on shuttles. A new control system must be installed and commissioned to control the overall operation of the manufacturing line. Fig. 2 shows the layout of the production system.



Note: The Saw, Router, Drill & Edger can carry out two different operational tasks.
The Gates can carry out four different routing tasks.
Shuttles will automatically advance unless held at a stop control actuator or are present in a queue.
The conveyor system can accommodate up to eight shuttles.

Fig. 2. Layout of MDF panel production system.

(a) Describe the type of control hardware that would be required to sequence the overall operation of this system. List the features of the hardware that make it suitable for this purpose. Highlight the location of any additional hardware such as sensors, shuttle control actuators or tracking devices required for the purposes of controlling the route of shuttles around the conveyor. [40%]

(b) Draw a system's architecture diagram that shows how the control software could be split into modules. List the functionality of each module and the benefits that this type of modular architecture provides. Discuss the overarching control strategy that could be implemented to ensure individual shuttles are moved via customised routes through the different production resources. [40%]

(c) When planning a systems development / integration project such as this, list the milestones that would be important in ensuring the success of the project. [20%]

Comment

Few students answered this question. As with questions 1 and 5, parts (a) and (b) of this question also had a 'strategy and detail' structure to them and though the answers were very good in parts, no answer was good everywhere. Part (c), which asked for a list of milestones to guide a development/integration project implementing a system of the kind described in the question, was addressed well by some but almost not addressed at all by others.

Answer

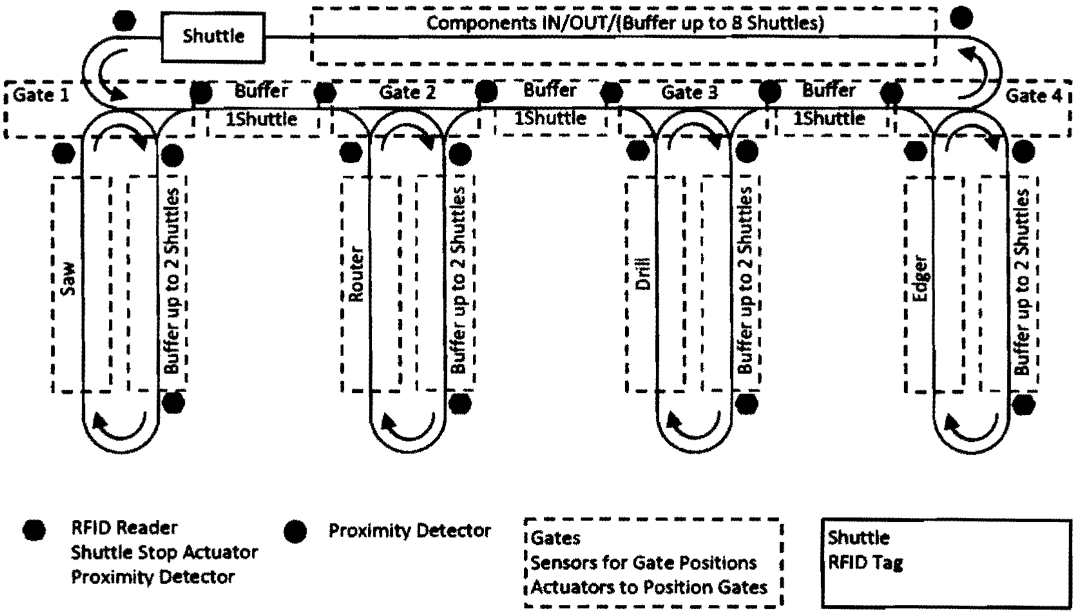
a. Automation systems such as the MDF production system can be controlled by a Programmable Logic Controller (PLC). PLC's can be configured with Input / Output cards allowing them to monitor sensors and control actuators at different locations around the conveyor. The PLC can run control code called Sequential Function Charts (SFC) which can sequence operations depending on the status of the system. In this system, proximity detectors are positioned in key locations (Discussed Later) on the conveyor / gates and wired back to the input module of the PLC. Actuators that control the operation of the gates and stop actuators for the shuttles would be wired back to the output module of the PLC. (In some cases such as in the lab, actuators are controlled electro-pneumatically requiring the use of pneumatic valve blocks and pistons.)

   Specific hardware such as the Saw, Router, Drill & Edger must communicate back to the PLC either via a commercial network such as device net or via dedicated I/O connections. These communication mechanisms must support protocols that allow a machine to be instructed to perform either of its tasks as well as providing information about its current status, E.g. PLC-Device (Run, Task 1) Device-PLC (Running / Finished) and (Error information).

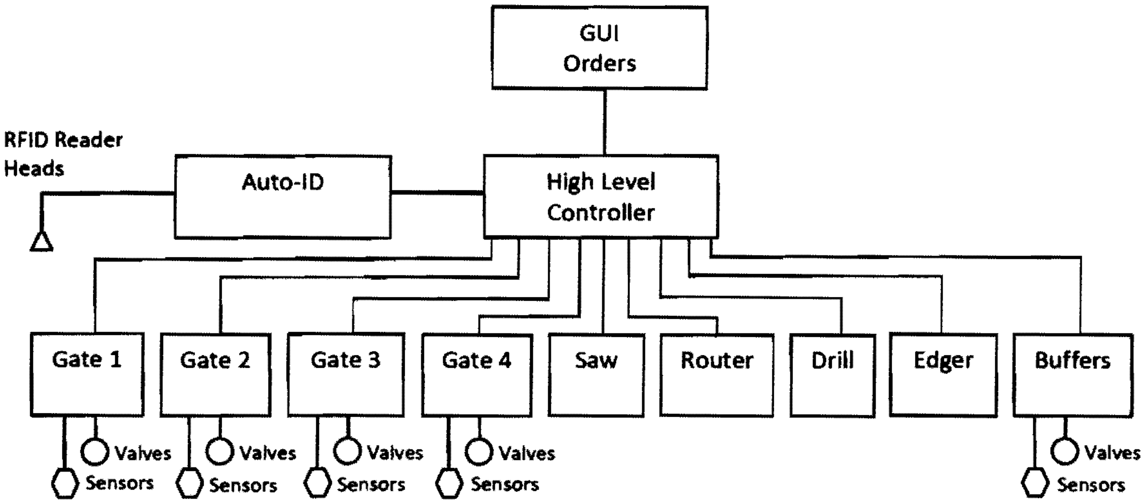
Due to the flexible nature of the MDF production system it is essential that the control system can move shuttles via different routes. This means that shuttles will have to be tracked / identified at key locations around the system. Many different Auto-ID types of solution could be used, but in this case I would use RFID as it is robust to the environment, a limited number of shuttles need to be tagged and information can be stored and updated on the tag as it moves through the system. The PLC can be configured to use RFID allowing RFID read-heads to be positioned at key locations (Discussed Later) on the conveyor and connected back to the PLC.

The following table lists the key features that make PLC's suitable for this task.

Feature	Description of Functionality
Determinist Operation	PLC's are designed to run code within a known time frame therefore ensuring that physical operations can be detected and acted upon appropriately. When PLC code is being tested the Scan time can be optimised to the application being controlled.
Robust Failure Modes	PLC's and their associated modules are very robust to failure but even when they do fail, they are designed to fail in a specific mode. Electro- mechanical systems in the factory can be designed with this in mind to ensure failures are handled in a safe manner.
Built for Industrial Environment	PLC's have no moving parts like hard disks and are enclosed in IP rated cases so that they can better cater for harsh industrial environments.
Graphical Programming Languages	Typically PLC's are programmed using Graphical User Interfaces such as Sequential Function Charts (SFC's) / Ladder Logic. These are widely adopted in the automation field and many automation engineers are familiar with their use.
Modular hardware for Automation needs	PLC's can come in a number of formats (Micro PLC's) with dedicated limited functionality, through to larger scale PLC's that are modular. Over the years specific modules have been developed for PLC's allowing the control hardware to be customised for specific needs. These modules include I/O, Temperature Loggers, A to D converters, D to A converters, Auto-ID, Vision System......(Growing daily and easy to integrate)
Deterministic Network support for Automation Equipment	As discussed previously deterministic operation is core to the functionality of PLC's. This extends to the network modules that can be added to the PLC. These networks make it easy to integrate with different pieces of equipment that use specific automation network standards, E.g. Device Net, Compo net or even EthernetIP.
Long life time of compatibility	Technology vendors such as Omron, Fanuc, and Siemens pride themselves on the scale of backward compatibility they provide on their platforms. This enables systems to be upgraded or extended over a long timescale.



b. The following systems diagram shows a potential way that the control software could be modularised. The modules have been focused around the hardware functionality.



The following table lists some of the functionality of the different software modules.

Software Module	Module Functionality
Gate 1	Gate code controls the low level operation of the gates, ensuring that they can be switched into any of the four operating positions. Sensors are used to ensure that the operational position can be determined. The control code provides a simple interface to the high level controller. This allows the high level controller to request a particular switch option to be performed. The gate controller also monitors the status of the gate, determining / communicating status and error conditions back to the high level

	controller.
Gate 2	Same as Gate 1
Gate 3	Same as Gate 1
Gate 4	Same as Gate 1
Saw	Saw code provides an interface to the operation of the saw machine. This ensures that the hand shaking protocol used by the saw can be interfaced into the protocol used by the high level controller. Depending on the specific operation of the Saw, it may be necessary to incorporate some additional control logic to release parts from the saw's up-stream buffer. It is also necessary for the saw to monitor the status of the gate before finished parts are released.
Router	Same as the Saw, but customised for Router's operations.
Drill	Same as the Saw, but customised for Drill's operations.
Edger	Same as the Saw, but customised for Edger's operations.
Auto-ID	The Auto-ID module ensures the correct operation of the RFID readers providing a mechanism for information to be written to shuttle tags as well as allowing shuttle tag and location information to be passed to the high level controller. The Auto-ID system will allow shuttle status information to be read, filtered and updated at decision points around the conveyor.
High Level Controller	The high level controller is really the brain of the system. This is where the control strategy for the system is implemented. The high level controller has standard mechanisms that can be used when talking to the other modules. (The control strategy implemented in the high level controller will be discussed below.)
GUI / Order Management	The Graphical User Interface (GUI) will provide a user interface to the system, allowing the status of the system to be displayed as well as allowing orders to be entered into the system.

The following table lists some of the benefits that modular software control architectures provide.

Manageable Development	The control system can be broken down into manageable chunks. This helps in the management, development and testing of the different software components.
Upgradability / Future Proofing	Software components can be developed with specific requirements in mind. Modules of code can be developed to control specific hardware components and specific processes. This ensures that upgrades to hardware components or system functionality can be adopted more easily without rewriting the whole control system.
Re-use / Reduce Develop-ment Time	Production systems are often comprised of duplicate production resources (in this case, four duplicate conveyor gates). A module of control code can be developed for a single gate and then re-used.
Robustness	Code developed in this way tends to be more robust as individual modules of code can be extensively tested.
Faster Integration / Commissioning (Test)	During the system integration and line commissioning activities, well developed modular code can normally be easier to test and debug. Errors and problems can be pinpointed more quickly.
Support	Well-structured and modular code is easy to document and maintain over time. (Enhancements / system changes can be isolated!!) Modular code development can be more easily broken

	down across a team of people.

To ensure that the maximum flexibility of the production system is obtained the following control strategy is adopted. Key to this strategy is the use of RFID and the ability to be able to uniquely identify shuttles in different states at different locations (decision points) around the conveyor. The conveyor layout is made up of a main loop that can be used as a feeder / buffer loop and four sub- loops allowing the different production resource to be accessed. Gates on the main loop can be used to divert shuttles into the sub-loops. Effectively the system circulates shuttles around the main loop until the appropriate machine feeder buffer is free on the appropriate sub-loop.
The shuttles are fitted with RFID tags and is initiated / programmed as orders become available. The tag is programmed with a recipe of operations to be performed. e.g. 1,3,4,8 as the shuttle reaches gate 1 on the main loop. An operator would have to load new material onto the shuttle and confirm this action on the GUI.
As a shuttle reaches a decision point on the main loop, the shuttle control actuator automatically stops the shuttle. A proximity detector is activated, triggering the high level control code to interrogate the Auto-ID module about which operation needs to be performed on the shuttle. Depending on the result the high level controller will instruct the gate to switch to either divert or straight-on option. Once the gate is switched to the required position the shuttle control actuator is triggered allowing the shuttle to continue. This principal is adopted at each decision point on the system. Gate 1 switches for operations 1 & 2 (Saw), Gate 2 switches for operations 3 & 4 (Router), Gate 3 switches for operations 5 & 6 (Drill) and Gate 4 switches for operations 7 & 8. Once the operations have been completed, the RFID information on the tag is updated. Once a shuttle has passed through all the operations required it stops on the main loop at gate 1. An operator replenishes materials and updates the system via the GUI.
A number of priorities may have to be programmed into the system to ensure that no subtle deadlocks occur. When shuttles are waiting at both inputs to a gate it may be prudent to prioritise the shuttle on the sub-loop to be released first. This system does not allow for optimum scheduling but does provide a simple flexible shuttle routing solution.

c. The following table lists the milestones that are important when planning a systems development / integration project.

Specify	Obtain Requirement Specification from the customer
	Develop a System Specification and get it approved by customer
Prototype	Any high risk components may need to be prototyped to ensure specifications can be achieved.
Design	System Design, Detailed Design, Update design from any testing.

Procurement	Buy any long-lead time components, Schedule outsourced components to be manufactured .
System Build	Manufacture / Build System (This is the 60% completion point on most projects).
Integrate	Structured Sub-System test plan, Sub-System Integration.
Test	Module and Unit Test, Factory Acceptance Test, Site Acceptance Test