Version WON/3

MET2
MANUFACTURING ENGINEERING TRIPOS PART IIA

Friday 29 April 2022 9.00 to 10.40

Paper 2

MODULE 3P2: OPERATION AND CONTROL OF PRODUCTION MACHINES AND SYSTEMS

*Answer **two** questions, one from each of sections **A** and **B**.*

*Answers to sections **A** and **B** must appear in separate booklets.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of a question is indicated in the right margin.*

*Write your candidate number **not** your name on the cover sheet.*

STATIONERY REQUIREMENTS
8 page answer booklet x 2
Rough work pad

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Engineering Data Book

10 minutes reading time is allowed for this paper at the start of the exam.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

You may not remove any stationery from the Examination Room.

Crib Q1

1 (a) Machining economics is an important topic to consider when planning production operations.

(i) In machining operations, explain why high production rates do not necessarily mean low production costs. [10%]

(ii) Discuss the three main types of tool wear encountered in machining operations and their impact on the process. [15%]

(iii) Briefly describe three measures can you take to extend tool life. [15%]

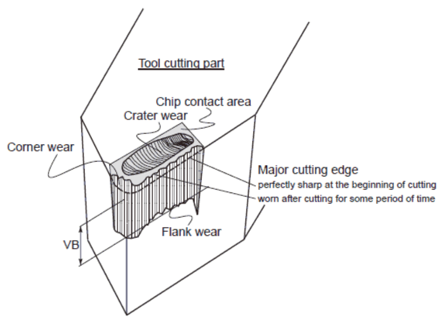
i)
Although in practice a high production rate would probably mean low production costs, these two factors must be considered separately and that the manufacturing conditions giving maximum production rate will not be identical to those conditions giving minimum cost of production.

In general, the production of a component will involve several machining operations using a variety of machine tools. Cutting speeds and feeds (cut depths) can be increased to increase production rates, and one could argue, reduce costs. However, with these considerations in mind it may be stated that in any operation, when the cutting speed is increased while the other condition is held constant, the actual machining time will be reduced, and the tool-wear rate will increase. Thus, very low speeds and feeds will result in a high production time because of the long machining time. Alternatively, very high speeds and feeds will result in a high production time because of the frequent need to change cutting tools. Clearly, an optimum condition will exist giving minimum production time. Similarly, an optimum condition will arise for minimum production cost. At low speeds and feeds costs will be high because of the cost of using the machine and operator for the long machining times. At high speeds and feeds costs will be high because of the cost of frequent tool replacement. The manufacturing engineer's problem is how to minimize both the production time and the production cost. Since, in general, these objectives cannot be reached simultaneously, a compromise must be sought.

Examiners note: better answers will cite the optimum speed Vc for minimum costs, and optimum speed Vp for maximum rate and include a graphic to show their relationship, as shown here from the notes.

ii) Gradual wear occurs at three principal locations on a cutting tool. Accordingly, the types of tool wear can be distinguished,

- Flank wear
- Crater wear
- Comer wear

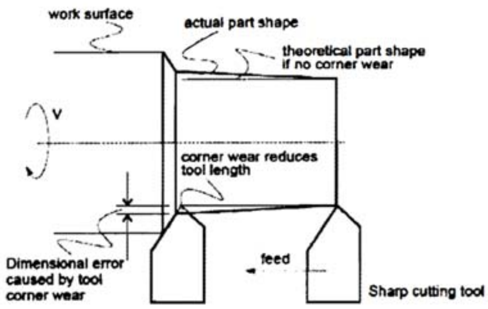


Types of wear observed in cutting tools

Where **Crater wear**: consists of a concave section on the tool face formed by the action of the chip sliding on the surface. Crater wear affects the mechanics of the process increasing the actual rake angle of the cutting tool and consequently, making cutting easier. *At the same time, the crater wear weakens the tool wedge and increases the possibility for tool breakage. In general, crater wear is of a relatively small concern.*

Flank wear: occurs on the tool flank because of friction between the machined surface of the workpiece and the tool flank. Flank wear appears in the form of so-called wear land and is measured by the width of this wear land, VB, Flank wear affects to the great extent, the mechanics of cutting. *Cutting forces increase significantly with flank wear. If the amount of flank wear exceeds a critical value, VB >0.5 ~ 0.6mm, the excessive cutting force may cause tool failure.*

Corner wear: occurs on the tool comer. Can be considered as a part of the wear land and respectively flank wear since there is no distinguished boundary between the comer wear and flank wear land. We consider comer wear as a separate wear type because of its importance for the precision of machining. *Comer wear actually shortens the cutting tool thus increasing gradually the dimension of the machined surface and introduces a significant dimensional error in machining, which can reach values of the order 0.03-0.05 mm.*



Examiners note: better answers will use sketches to support their arguments

iii)

Examiners note: I have given a number of options below with commentary

Control the Heat

During the cutting process, the friction of the chip removal generates heat. Over time, this heat can wear away your tools. For this reason, it's important to control the generated heat as much as possible. A coolant system utilizing CO_2 can help control the amount of heat generated during the cutting process, which will minimize the damage done to the tool.

Prepare the Edge

Edge preparation mostly involves removing material from the cutting tool. This process is important to minimize the possibility of edge chipping that can lead to tool failure. Preparing the edge will strengthen the edge in order to minimize this damage. There are different tactics to prepare the edge of the material, including brushing and nylon filament brush honing.

Design Tools Properly

One of the best ways to ensure a tool is long lasting is to ensure that it has a proper design. Cutting tools need to achieve high metal removal rates with minimum stress on the tool. These tools need to be able to handle the stress of simultaneous, multi-directional movements. A properly designed tool will be able to hold up to the stresses of the job without being damaged.

Coating the Inserts

Special coatings will help avoid heat damage to your cutting tool. There are many different coatings that are used on cutting tools, with the main coatings being CVD and PVD coatings. CVD coatings are thicker with good wear resistance; however, they do not adhere well to sharp edges. PVD coatings are thinner, but can better adhere to sharp edges and are easier to apply. Both of these coatings are suitable for different applications, but both will help avoid heat damage to your cutting tools.

Use the Right Feeds and Speeds

It's important to look up the correct feeds and speeds for your tools and for each metal your tool cuts. When tools are used at the wrong feed or speed, it can lead to damage of the material and the tool itself. Although you might think the sound and look of the cut is enough to judge if it's correct, sometimes you will not notice the damage that is occurring. To avoid this damage and extend the life of your tool, look up the feeds and speeds ahead of time and enter the right ones into the computer program.

Lubricate Sticky Materials

There are certain materials that will be prone to stick to the material the cutting tool is made of. When this sticking occurs, it can weld chips onto the cutting edge and damage the tool. With sticky materials, it's important to lubricate the materials to prevent these issues. Flood coolant, mist coolant, and tool coatings can all provide this lubrication. Lubricating sticky materials is an effective way to extend the life of your cutting tools.

Be Gentle When Entering and Exiting the Cut

A significant amount of damage to cutting tools is done when initially entering or exiting the cut. On tougher materials, entering the cut can even chip an edge of the tool. To avoid this damage, you should avoid plunging the cutter and enter and exit the cut gently. Using a ramp, helix, or spiral can help ensure gentler entry and exit of cuts. For profile cuts and surfacing, consider arcing into the cut. Another way to ensure a gentler entry is to use an indexable drill to create a hole for entry. Gentle entry and exit of a cut can help prevent damage to the cutting tool and extend its life.

(b) The average production cost of a component can be written as.

$$C_{pr} = Mt_l + Mt_m + M\frac{N_t}{N_b}t_c + \frac{N_t}{N_b}C_t$$

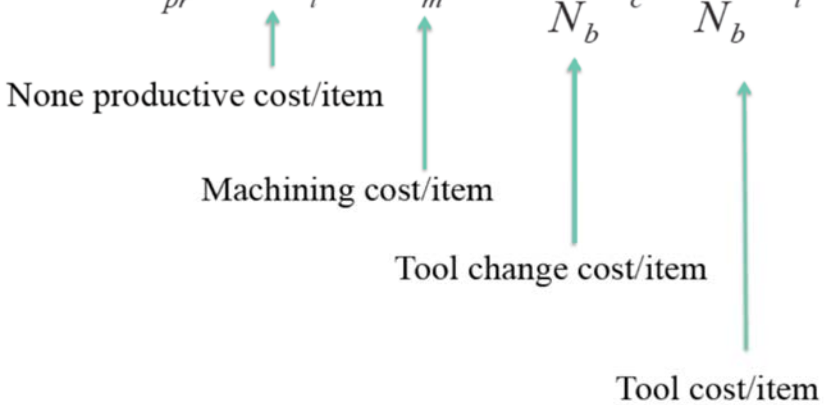
where M is the machine and operator charge rate, t_l is the time to load and unload the part, t_m is the time to machine the part, t_c is the time to replace a worn tool, N_t is the total number of tools used in an entire batch, N_b is the number of parts in the batch, and C_t is the cost of each tool.

(i) A cylinder of diameter 150 mm is rough turned to a diameter of 142 mm over a length of 200 mm. The following conditions apply, C_t = £20, M = £80/h, t_l = 26 s, t_c = 3 min. The maximum feed for the cutting tool is 0.35 mm with a maximum depth of cut of 2 mm. Taylor's tool life conditions are, n = 0.2, with T = 60 s, and V 4 m/s. Calculate the average production cost for cutting speeds of 1.2, 1.6, and 2.0 m/s. Comment on the trends you observe. [40%]

(ii) What methods could you employ to monitor tool wear? [20%]

i) The expression provides us with the following information

$$C_{pr} = Mt_l + Mt_m + M\frac{N_t}{N_b}t_c + \frac{N_t}{N_b}C_t$$



We need to develop this expression further to make it useful for the calculations. Firstly we need to calculate the number of tools used. We need to use a modified version of Taylor's tool life equation:

$$\frac{v}{v_r} = \left(\frac{t_r}{t}\right)^n$$

Where v is the cutting speed, t is the tool life, n is a constant, and t_r is a measured tool life for a given cutting speed v_r.

The number of tools N_t used in machining the batch of components is given by

$$N_t = \frac{N_b t_m}{t}$$

Combining these two expressions gives

$$\frac{N_t}{N_b} = \frac{t_m}{t} = \frac{t_m}{t_r}\left(\frac{v}{v_r}\right)^{1/n}$$

and

$$C_{pr} = Mt_l + Mt_m + M\frac{N_t}{N_b}t_c + \frac{N_t}{N_b}C_t$$

Finally, the machining time for one component is given as

$$t_m = \frac{L}{v}$$

Where v is cutting speed and L is a constant that determines the full cutting length. In our case where we have a turning operation L is given by

$$L = \frac{\pi d_w l_w}{f}$$

Where d_w is the diameter of the workpiece, l_w is the length to be turned and f is the feed.

Our average cost per part equation then becomes

$$C_{pr} = Mt_l + MLv^{-1} + \frac{L}{v_r^{1/n} t_r}(Mt_c + C_t)\, v^{1-n/n}$$

In the case of our calculation
Where now

$$L = \frac{\pi d_w (2l_w)}{f}$$

Since we need two passes to reduce the diameter to the required dimension as max cut depth per pass is 2mm. *Note: this approach ignores the indexing time back to the start position which we assume to be very small compared to the time for machining.*

Given

M = 60/3600 = £0.0166/s
t_l = 26 s
v_r = 4 m/s
t_r = 60 s
n = 0.2
t_c = 180 s
C_t = £20
d_w = 0.15 m
l_w = 0.2 m
f = 0.00035 m
L = 538.62 m
V = 1.2, 1.6 and 2 m/s.

For a speed of (1.2 m/s) the cost per item is

Cpr = 0.43 + 7.45 + 0.01 x (2.98+20) x 2.07 = **£8.3**

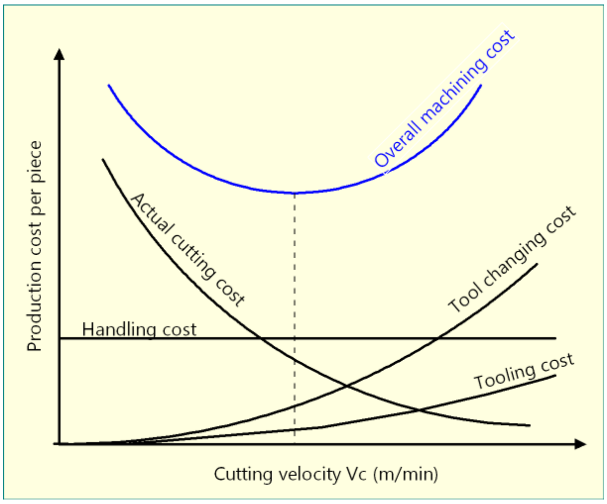
For a speed of (1.6 m/s) the cost per item is

Cpr = 0.43 + 5.58 + 0.01 x (2.98+20) x 6.55 = **£7.34**

For a speed of (2 m/s) the cost per item is

Cpr = 0.43 + 4.47 + 0.01 x (2.98+20) x 16.00 = **£8.57**
£8.12

Comment: from the data it looks like we are close to the optimum cutting speed for minimum cost, since we have a minimum near 1.6 m/s, as shown in the sketch.



ii)
Tool Life Monitoring could be employed to monitor tool wear
There are a collection of technologies that can be used to monitor with Tool Wear. Answers could include:

- Usage Tracking in the Machine's Tool Table. The total number of minutes a tool has run may be tracked by more modern CNC machines. This number can be accessed via system variables and the g-code can choose to use a different tool or call for the operator to change the tool when total run time reaches a threshold.
- Digital Probes can check wear, breakage, and chipping on the edge of a tool. When the measured diameter changes too much from a given value, the tool can be deemed worn and a replacement called for.
- In some cases, spindle load monitoring can be the early tip off for tool wear since cutting forces increase as the tool wears.

Examiners note:

This question related to the economics of machining operations with a broad spectrum of responses. Part a) was answered reasonably well with most candidates able to discuss the relationship between production rate and production costs. A good knowledge of tool wear mechanisms was evident across the class, although many gave confusing answers on the measures that could be taken to extend tool life. Part b) proved to be more challenging. With low scoring answers being unable to develop a general expression for tool costs resulting in answers that were wide of the mark. Part bii) proved to be a challenge for some candidates, that failed to identify suitable means of monitoring tool wear as discussed in the lectures.

Q2 Crib

2 (a) (i) If softer materials like aluminium and copper are easier to machine, and materials tend to soften with increasing temperature, why is it undesirable to allow temperatures to rise in machining operations? [10%]

(ii) Explain how cutting fluids can influence the magnitudes of the thrust force F_t, and cutting force F_c. Use diagrams to support your answer. [15%]

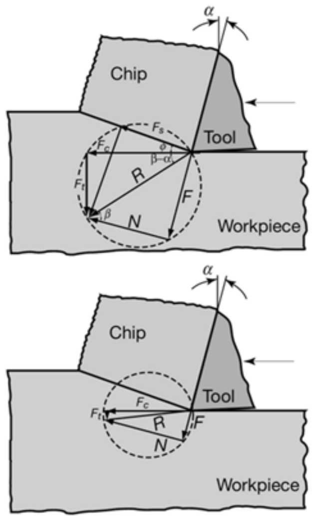
(iii) Why is it important to have knowledge of the magnitude and direction of the thrust force F_t? Under what conditions can this force be upward? [15%]

a)

i) There are large number of acceptable answers, but the main arguments are:

a) Heat generated during machining results in tool wear eventually leading to high surface roughness of workpiece.
b) Chemical reactivity generally increases with increasing temperature, thus in-creasing the wear rate.
c) The effectiveness of cutting fluids can be compromised at excessive temperatures.
d) High temperatures will cause dimensional changes in the workpiece, thus reducing dimensional accuracy.
e) Excessively high temperatures in the cutting zone may induce metallurgical changes and cause thermal damage to the machined surface, thus affecting surface integrity.

ii) The use of a cutting fluid will reduce the friction force, F, at the tool-chip interface. This, in turn, will change the force diagram, hence the magnitude of the thrust force, Ft. Consider the sketch given below. The upper sketch shows cutting without an effective cutting fluid, so that the friction force, F is large compared to the normal force, N. The lower sketch shows the effect if the friction force is a smaller fraction of the normal force because of the cutting fluid. As can be seen, the cutting force is reduced when using the fluid. The largest effect is on the thrust force, but there is also a noticeable effect on the cutting force.



iii) Knowledge of the magnitude of thrust force is important because the tool holder, the work holding and fixturing devices, and the machine tool must be sufficiently stiff to minimise deflections caused by this force. If not the tool could be pushed away from the workpiece, reducing he depth of cut, leading to dimensional accuracy, possibly leading to vibration and chatter. It can be shown that the sign of Ft can be +ve or -ve by observing that

$$Ft = R\ sin(\beta - \alpha)$$

or

$$Ft = Fc\ tan(\beta - \alpha)$$

The sign of the thrust force can be +ve or -ve of the

Since Fc is always positive, the sign of Ft can be either positive or negative. When $\beta > \alpha$ the sign of Ft is positive (downward), when $\beta < \alpha$, it is negative (upward). Thus it is possible to have an upward thrust force at low friction at the tool chip interface and/or high rakes angles.

(b) A machining operation is being carried out with the conditions shown in Table.1.

Undeformed chip thickness t_o	0.6 mm
Chip width w	2.54 mm
Cutting ratio r	0.3
Cutting speed v	91 m/min
Rake angle α	0°
Cutting force F_c	890 N
Thrust force F_t	667 N
Workpiece density ρ	7.8 g/cm^3
Workpiece specific heat capacity C_p	502 J/kg°C

Table 1

You may assume the following: the sources of heat are from the shear plane and tool-chip interface; the thermal conductivity of the tool is zero and there is no loss of heat to the environment; the temperature of the chip is uniform throughout.

(i) Determine the total power dissipated in the shear zone. [30%]

(ii) If the average temperature rise of the chip is 135 °C, what is the percentage of total power dissipated in the shear zone that is lost to the workpiece? Comment on your answer. [30%]

i) Power dissipated in the shear zone is

$$P_{shear} = F_s V_s$$

Where, from the force balance

$$F_s = Rcos(\phi + \beta - \alpha)$$

and

$$R = \sqrt{F_c^2 + F_t^2} = 1112.2\ N$$

From merchants model we can deduce that

$$\phi = tan^{-1}\left(\frac{r\cos\alpha}{1 - r\sin\alpha}\right)$$

$$\phi = tan^{-1}\left(\frac{0.3\cos 0}{1 - 0.3\sin 0}\right)$$

$$\phi = 16.7^o$$

To find Fs, we need to determine β, this can be done as follows.

Examiners Note: If Merchant's relationship is used to obtain β, candidates MUST justify their choice, and state the likely error in predicting β.

From merchants model we can deduce that

$$F_c = R\cos(\beta - \alpha)$$

Solving for β

$$\beta = \cos^{-1}\left(\frac{F_c}{R}\right) + \alpha$$

$$\beta = \cos^{-1}\left(\frac{890}{112.2}\right) + 0$$

$$\beta = 36.85^o$$

Therefore

$$F_s = 1112.2\ cos(16.7 + 36.85 - \ 0) = \ 661\ N$$

From merchants model we can deduce that

$$V_s = \frac{V\cos\alpha}{\cos(\phi - \alpha)} = \frac{91\cos 0}{\cos(16.7 - 0)}$$

Or V_s = 95.1 m/min

Therefore

$$P_{shear} = F_s V_s = \ (661)(95.1)$$

$$P_{shear} = 62861\ (N - m/min) = \ \mathbf{1.048\ kW}$$

Examiners Note: 1 Watt is equal to 60 N-m/min

Part ii)
The volume rate of removal is

$$V_{vol} = V \cdot t_0 \cdot w = \ 9100 \cdot 0.06 \cdot 0.254 = 138.69\ \ cm^3/min$$

The energy/min received by the chip, Q
$Q/min = MC_p\Delta T = \ $ ((0.0078 · 138.67) · 502 · 135= 73301 J/min
Power dissipated in the P_{chip} = 73301/60 = 1,22 J/s = 1.22 kW

Total power dissipated
$P_{total} = F_c V = \ 890 \cdot 1.51 = \ 1.34$

Hence heat dissipated into the workpiece is
(1.34 – 1.22) = 0.12 kW

This is 0.12/1048 = 0.11 = **11%** of the energy dissipated in the shear zone is lost to the workpiece.

Comment. This is a reasonable percentage since most of the heat is taken away from process by the chip.

Examiners Note:
This question related to an analysis of forces in machining operations. Part a) focused on the effects of temperature in machining operations and cutting forces. Most candidates scored well in this section and demonstrated a good knowledge of Merchant's force circle and how to apply it. Part b) required candidates to calculate the power dissipated in the shear zone. There were many good answers and rather few excellent answers. This was in part due to the lack of knowledge of the velocity relationships in the process. The thermodynamic analysis in part bii) was answered reasonably well with some candidates failing to apply the appropriate energy balances to determine the percentage power dissipated in the shear zone that is lost to the workpiece.

SECTION B

3 (a) (i) What is *handshaking* in the context of an automated production operation?

(ii) Why is handshaking used?

(iii) What are the benefits and downsides of handshaking?

[20%]

i) Handshaking involves the introduction of an additional signal between two devices to confirm connection. In industrial automation situations this is often between a machine and a PLC confirming that an operational signal (e.g. START, STOP) has been received and that the required operation is proceeding.

ii) Handshaking is used - along with other measures - as a safeguard to ensure that a communication has been received and the instructions have been received correctly

iii) Benefits
- reliability - avoid incorrect operations
- productivity - avoid stoppages
- safety precaution
- fault detection and diagnosis

Downsides
- addition coding
- increased complexity
- handshaking perceived to address all safety concerns

(b) A system involving two robots and a conveyor has been developed in a warehouse for extracting priority goods from the main conveyor system. The system is illustrated in Fig 1 in which available priority boxes are received by the loading robot and placed on the conveyor at position A. On detecting the box at A, the conveyor motor is turned on and the box proceeds to position B. On detecting the box at B, the conveyor motor is turned off and the box is retrieved by the unloading robot. For additional safety both robots must have returned to their home position before the conveyor starts, and the conveyor must be confirmed idle before either robot can operate. Only one box at a time can be processed by this system. Inputs to and outputs from the controlling PLC are as follows:

Inputs
I0: Priority box available for loading (external signal)
I1: Loading robot in home position
I2: Box detected at input – Posistion A
I3: Box detected at output – Position B
I4: Unloading robot in home position
I5: Conveyor stationary

Outputs
O1: Conveyor motor on
O2: Loading robot on
O3: Unloading robot on

(i) Identify the states of each robot, the conveyor and the box.

(ii) Determine the valid states of the system that a box moves through and sketch a state machine diagram. Annotate your diagram with the system inputs and outputs given above.

(iii) Generate Ladder Logic that could be used on the PLC controlling the system.

[50%]

i)

Loading robot states: (Loading, Homing, Idle)
Unloading robot states: (Unloading, Homing, Idle)
Conveyor states: (Operating, stopped)
Box states: (ready to load, loading, on conveyor, unloading)

Students might choose to produce state machine diagrams to represent the states of each element and these provide a suitable response provided the states are clear.

Students might also produce constraint / prerequisite analysis for each resource which will yield the same outcomes and can be used in the next section

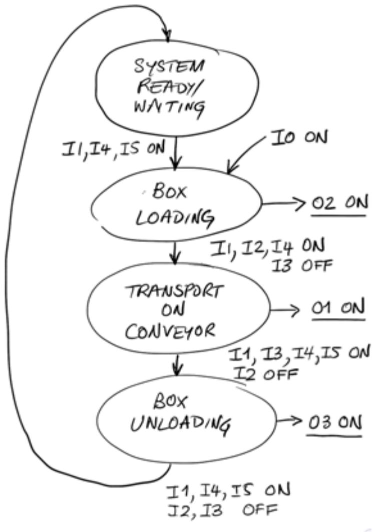
ii)

There are potentially some variations allowable in this response, especially where different states have been identified in part i). A typical answer will include:

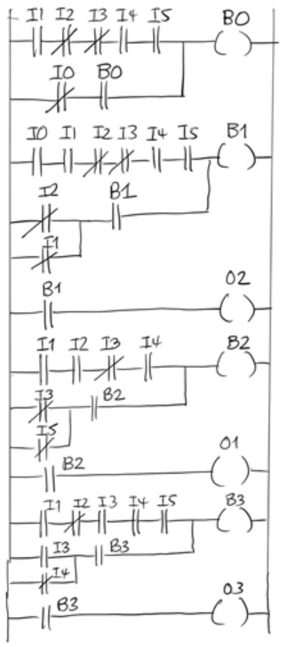
SYSTEM STATE	*INDIVIDUAL STATES*
B0: System ready / waiting	*Loading robot states: (Idle)* *Unloading robot states: (Idle)* *Conveyor states: (idle)* *Box states: (ready to load)*
B1: Box Loading	*Loading robot states: (Loading, homing)* *Unloading robot states: (Idle)* *Conveyor states: (Idle)* *Box states: (loading)*
B2: Transporting Box on Conveyor	*Loading robot states: (Idle)* *Unloading robot states: (Idle)* *Conveyor states: (Operating)* *Box states: (on conveyor)*
B3: Box Unloading	*Loading robot states: (Idle)* *Unloading robot states: (Unloading, Homing)* *Conveyor states: (Idle)* *Box states: (unloading)*

It is noted that there are potentially other intermediate temporary states which might be added to differentiate between loading and homing of robots and the arrival of a box at conveyor exit and the commencement of the unloading process.

A sketch of a possible state machine representation is:



iii) There are also multiple valid options for a piece of ladder logic to control the operations of this system. The ladder code presented here aligns as closely as possible with the state machine in ii).



(c) Stating any assumptions, describe the additional considerations required for the system in b) to allow the conveyor to handle two boxes at a time, so that a box can be loaded to the conveyor at the same time as another is being unloaded. The conveyor is assumed to be long enough that the two robots will be able to operate independently.

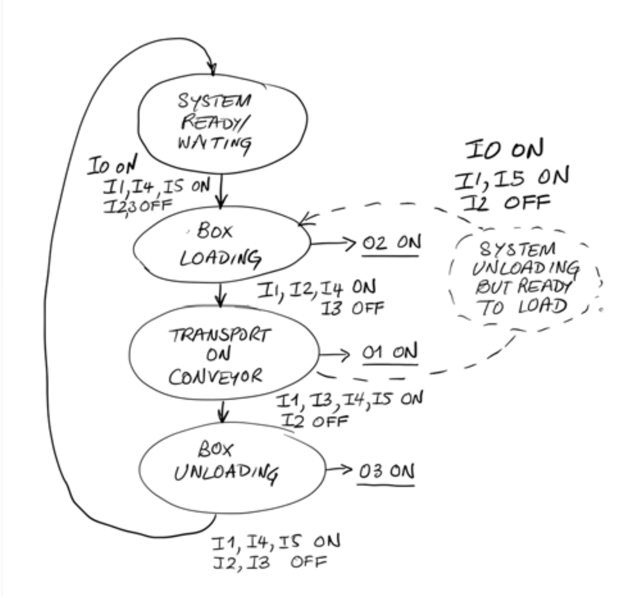
[30%]

There are numerous ways to make this type of extension and some of the general possibilities are covered by the following:

Assumptions:
- conveyor must be stopped for either loading or unloading or both
- the two robots are permitted to move simultaneously if required
- both robots must be idle before the conveyor can move
- the conveyor cannot be stopped for loading i.e. a box already on the conveyor must be at the exit point
- if needed, unloading takes priority over loading

Approach
- the state machine needs to be extended to allow for
loading only
unloading only
both unloading and loading
- conveyor state cannot be ON unless both robots IDLE
- loading can only be enabled by conveyor OFF signal

Good solutions are likely to show an amended state machine to show the change to the logic states. A simple amendment to the previous state machine in b) could be along the lines of *the diagram below although on reconsideration of the system it is clear that the loading / transporting operations effectively decouple from the unloading operation and hence a simple state arrangement might be determined.*



<u>Examiners Note:</u>
This question related to the automation of a conveyor loading process and a wide spectrum from very good to rather poor responses was provided. Section a) relating to handshaking was generally well answered albeit with a few students simply guessing about the process. Part b) then related to the automation of the conveyor process and students generally identified the states of the individual pieces of equipment very well and then had mixed success with developing state machine diagrams of the combined system. Many failed to fully annotate their diagrams. Subsequent ladder diagrams derived from the state diagrams were generally OK. The last section required students to consider an extension to this system. Many students simply seemed to have run out of time for this section and those few that attempted it fully did well.

4 (a) Explain what is meant by the term *digital manufacturing* and discuss the reasons for its development over the last ten years. [15%]

Different responses are acceptable here but definition and some key factors discussed in lectures:

Digital manufacturing is the application of digital information [from multiple sources, formats, owners] for the enhancement of manufacturing processes, supply chains, products and services

Two key reasons for its development

- technological advances in last 10 years
- *Internet is ubiquitous*
- *Network many devices / objects / data sources*
- *Cloud computing*

- *Mobile, personal computing*

- recognition of strategic importance of digital systems within companies

- *major shift from IT Services -> IT Strategy*
- *Information shareability across value chain now possible*
- *Order Information Orientation - orders and their elements are a defined IT entity in many cases linked to ...*
- *Customer involvement - customers in the loop via internet*

(b) A number of emerging digital technologies have been associated with the recent digital manufacturing developments. For three such emerging technologies:

(i) Describe their main features and benefits;

(ii) Identify new manufacturing solutions that they enable;

(iii) Discuss how each technology might align with one (or more) of the three dimensions associated with Industry 4.0.

[45%]

i) This table summarised a number of the different emerging technologies discussed in lectures. Others are also possible.

Technology	*Features*	*Benefits/Impact*
Digital Twin	*Product and / or process modelling real time data alignment*	*easier collaboration, anticipation & prediction of problems*
Cyber Physical System	*linked equipment and control functions intelligent operations*	*tighter management of machine operations*
AI	*human based reasoning at machine / product level*	*adaptability in face of disruptions, ability to learn/improve over time*
AR/VR	*virtual or augmented walk through capability*	*non intrusive training and maintenance on machines*
IoT	*connecting obects to networked data via wireless transmission/receipt and gateways*	*bringing the periphery of operations into network*
Machine Learning	*ability to develop and iteratively improve a model / pattern using real time data*	*accurate representation and matching of physical entities and digital representations*
Block Chain	*distributed, verifiable data and ledger management*	*secure, trustless, decentralised data management*
Cobots	*robot capable of working in same envionrment as humans*	*safe, productivity / accuracy enhancing,*

ii) This table summarised a number of the solutions associated with different emerging technologies. Others are also possible.

Technology	*Solutions*
Digital Twin	*Product design, process monitoring*

Cyber Physical System	*Machine / Cell control & management*
AI	*Factory / Line control, process improvement, autonomous operations*
AR/VR	*Inspection, training, maintenance*
IoT	*Sensing / analysis of tools, parts, products,*
Block Chain	*Supply chain data sharing, traceability, contracting*
Cobots	*Human task assistance (e.g. assembly)*

iii) There are basically three dimensions of Industry 4.0

- *Vertical integration and networked manufacturing systems*
- *Horizontal integration through value networks*
- *End-to-end digital integration of engineering across the entire value chain*

The table below outlines alignment of key technologies with Industry 4.0 including the emerging technologies discussed above.

Vertical integration	*Enabling manufacturing operations to be tightly connected to the business to respond to and drive business / market trends, events and decisions*	*AI* *Industrial internet* *Data analytics/ Machine learning* *Intelligent control & optimisation* *Human Machine interfaces* *Cyber physical systems* *Cobots* *Machine Learning*
Horizontal integration	*Enabling information and decisions relevant to specific products, orders and materials securely pass between different environments, organisations and operations in real time*	*IoT infrastructure* *Cloud based data management* *drones* *bluetooth/zigbee* *Automated identification* *Customer oriented systems* *Block Chain*
End-to-end digital integration	*Enabling digital information to be bound to a product such that its design and production and use are streamlined and continuously improved*	*integrated CAD/CAM* *process/product Simulation* *Digital twins* *Customer in Design* *Product Life Cycle Information*

Good responses will also discuss the way the technologies impact on each of the dimensions.

(c) An aerospace parts company is giving its machining operations an overhaul. A greater customisation of product lines is planned and hence smaller product batches, the use of multiple tools and different machine settings, and an increased number of production changeovers are expected. Further, a diversification of suppliers with more stringent delivery requirements is proposed which is expected to impact the quality of raw materials, and lead to more frequent, just-in-time deliveries.

(i) Making reasonable assumptions about the nature of the existing industrial automation and control facilities, what new digital solutions might be required to support these new developments? Justify the solutions you suggest.

(ii) Identify where emerging digital technologies (as well as more developed technologies) might be required to support the suggested solutions.

[40%]

the table below summarises the type of issues that will be raised in typical responses for both parts i) and ii)

New Development	*Specific Needs (i)*	*New Solutions (i)*	*Relevant Technologies (ii)*
greater customisation of product lines	• *smaller, customised product batches,* • *the use of multiple tools and different machine settings,* • *increased number of production changeovers*	• *Tracking of products in batches throughout operation.* • *Automated tool management system with automated tool selector* • *Automated / semi automated material handling, tool handling*	• *IoT sensors, RFID, machine learning to model product / production variations* • *Cyberphysical capabilities and potentially digital twin of the machine to manage the many changes* • *Robots/cobots to assist the changeover process*
diversification of suppliers	• *more stringent delivery requirements* • *quality of raw materials,* • *more frequent, JIT deliveries*	• *inbound delivery tracking system* • *need to access RM quality data quickly and to learn how changes affect production* • *schedules and material planning systems need to be more flexible*	• *3rd party IoT solutions to gather order tracking data from suppliers - especially location and ETA* • *Block chain or other RM traceability approach, and machine learning to learn effects of quality changes* • *use of AI based planning and scheduling tools that are aware of local variations and can adapt*

Examines Note:

This question was attempted by only 8 students and referred to material covered in the last lecture in the P2 course on digital manufacturing. In general responses were a little disappointing with limited technical detail to support a reasonably good general understanding of the area. Section a) on emerging technologies was generally quite well done. Students struggled more with section b) which presented a factory scenario and required analysis of solutions and their underlying technologies which might support factory improvements. Responses were also marred by rather poor clarity in responses. Again, students appeared out of time in completing this question despite rather short responses.

END OF PAPER