MANUFACTURING ENGINEERING TRIPOS PART I

April 2006

Paper P2

ORGANISATION AND CONTROL OF MANUFACTURING SYSTEMS

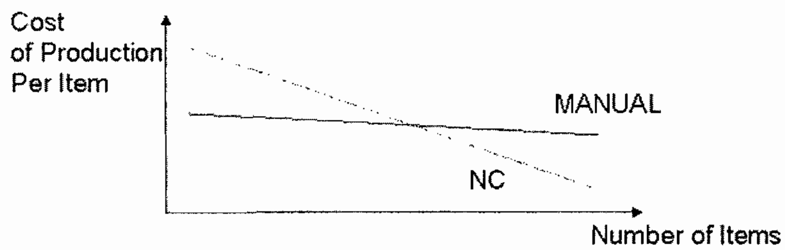
SAMPLE SOLUTIONS

Question 1

a) Benefits associated with CNC programming include:

- flexibility of operation
- ability to produce complex shapes
- easy to make machine adjustments
- reduced operator experience requirement
- reduced set up and fixturing time
- reduced number of set ups
- rapid preparation of programmes
- reduced tooling costs

Reasons for considering more manual approaches are summarised in the plot below (from lectures) and include: cost of one off jobs, cost of CNC machines in low volume environments and cost of operator training etc.



b) (i)

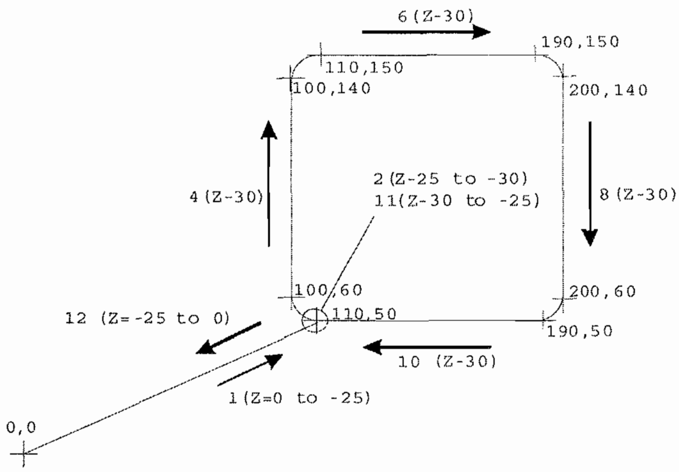
Key operations (book work)
setting positioning coordinates
move tool to position
turning on spindle
description of linear, circular paths for cutting

Note: good students described these operations clearly and demonstrated how they are being used in the context of the problem.

Required to complete programme (as a minimum)
- Return travel
- Spindle stop
- Programme complete

Also could have added
- Remove offsets
- Turn off swarf removal, lubricant

(ii) Diagram showing the tool traverse. (Current G – Code)



(iii)

There are a number of ways in which the production rate of this machine could be improved. Each of the following approaches gets more sophisticated enabling higher through puts, but requiring greater financial investment.

- physical hardware

Fixturing: The first and most basic approach would be to redesign the fixturing, allowing several castings to be clamped in place in one operation before the machine cycle commences. The CNC code would have to be updated depending on the style of fixturing used. Rotating a fixture block on a rotary table or repeating the machining profile at several locations across the work space of the machine bed would allow the operator to work more efficiently in performing clamp or unclamp operations and provide spare / meaningful operator capacity during the machining cycle. The use of interchangeable fixture blocks allows them to be unpopulated / populated during a machining cycle. At the end of the machining cycle the fixture blocks can be interchanged, enabling higher machine utilisation.

Material handling: To further increase the production rate with lower manpower we have to invest in some automated loading and unloading processes by making use of robotic systems. This also requires the use of part feeders, shuttle systems or conveyors to present parts to the loading stations where a robot can be used to load / unload parts into fixtures for the machining operation. The fixturing technology must be updated so that it can perform the clamping operation automatically; this can be done with a series of control valves and pistons using either hydraulics or compressed air depending on the machining forces.

- sensing
-

Now that we are moving to a more automated machining process it is important that we can detect all of the operations that are taking place and if they are occurring correctly. This will require the addition of various sensors to detect the presence of parts and to ensure that various clamps and mechanical systems are operating as required. It may also require more sophisticated sensors such as vision systems to detect the orientation of parts that need to be manipulated.

- control system

To link all of these operations together and ensure the correct sequence of tasks in the machining cell, it will be necessary to make use of a PLC (Programmable Logic Controller). This will be used to sequence the operation of the part feeders and sense when products are available to be loaded into fixtures. It will trigger the operation of the robots to do the load / unload cycle. Once the parts are correctly loaded and clamped in the fixtures, the machine tool will be triggered to perform the machining cycle, etc.

From an operational point of view control software will have to be developed to allow this operation to be linked into the control system of the production line. Error handling processes will have to be developed to ensure that any errors that occur during a machining process are catered for correctly by stopping the machining cycle safely and calling the attention of an operator or maintenance specialist as required.

The impact on manpower can be summarised by

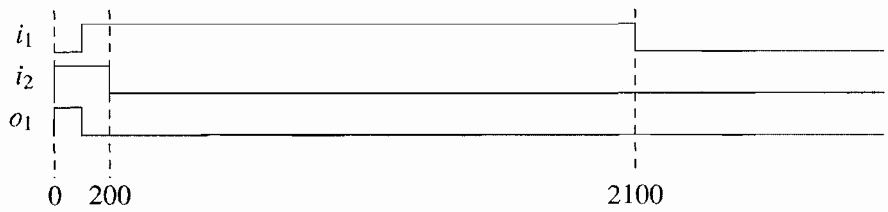
- less direct physical involvement in the operation – may lead to manpower reduction
- increased maintenance effort
- greater level of supervision required at IT level

[Good students discussed requirements at stand alone vs integrated operations]

Question 2

a)

The time line for the PLC inputs and outputs is given below: (X axis is time in milliseconds)

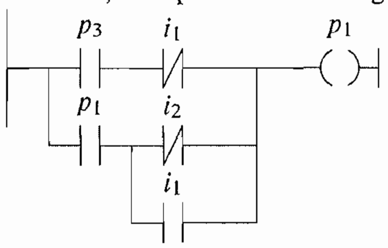


b)

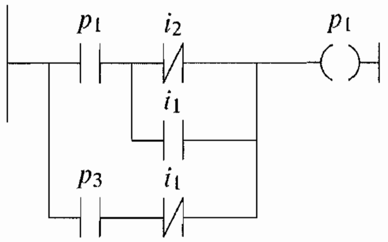
A simplified version of the Boolean equation given is

$$p_1 = p_1.(\overline{i_2}+i_1)+p_3.\overline{i_1}$$

From this, the equivalent ladder logic can be expressed as



or



Others alternatives may also exist but these are the most likely

c) The key here is to note that rungs are read sequentially in ladder logic. By introducing an additional logic step (rung 2) a state can be generated which is initially 0 but will become 1 for all time once rung 2 has been read. Hence it can be used to set p1=1 in the initial scan cycle

Rung 1: $p_1 = p_1.(\overline{i_2}+i_1)+p_3.\overline{i_1}+\overline{b_1}$
Rung 2: $b_1 = 1$

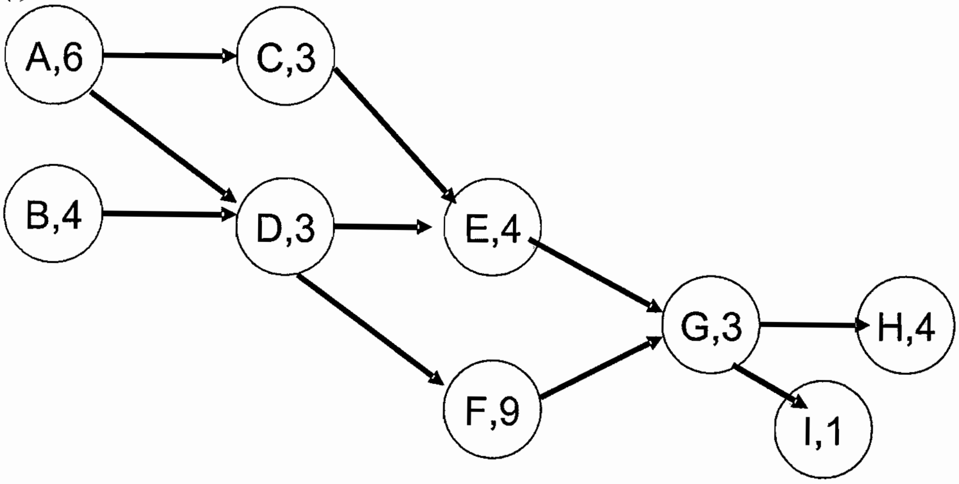
d)

The Petri net may cause the turntable to rotate several turns when only one was asked for, as it will leave O1 turned on well after I1 has turned off. Depending on the behaviour of the turntable, this may also cause a deadlock with a token at P2.

Question 3

a)

(i) The network is:



(ii)

The work content = Σp_i = 37 minutes
Cycle_time = (7.5 mins * 60) / 50 units = 9 minutes/unit

Minimum number of stations = Σp_i / cycle_time = 37/9 = 4.11,
i.e. min. 5 stations.

The line balancing can be achieved by either the **"longest sequential chain of followers"** or **"largest number of followers"** heuristics. Both heuristics yield the same solution.
[note: few students commented on why the had selected these approaches]

In either case, the minimum number of stations can be achieved by grouping them – for example - as:
Worker 1: (A,C)
Worker 2: (B,D)
Worker 3: (E,G)
Worker 4: (F)
Worker 5: (H, I)

(iii)

The minimum number of workers is 5

The balancing loss = 1- (Σp_i)/ (number of workers * cycle_time) = 1- (37/5 * 9) = 17.8%
Hence the system is not optimal – there is wasted manpower. The company might want to consider overtime / additional roles for some workers.

b) The main advantages of inventory holding:

- Ability to buffer against demand, production or supply uncertainty (=3 issues)

- Ability to run at economical lot sizes, and thereby reduce the opportunity cost of machine setup

- Ability to smooth production by levelling out demand with a response buffer
- Ability to use price reductions in the raw material market to purchase at lowest cost

The main disadvantages of inventory holding:

- Cost of capital to keep stock, and the cost of warehousing & associated labour, energy etc.
- Quality degradation due to stockholding
- Risk of obsolescence and depreciation of items in stock
- Stockholding masks problems, i.e. does not push people to improve manufacturing operations

c)
Doubling the line speed would mean a cycle time of 4.5 minutes – meaning a minimum of 9 workers will be needed – this follows from a repeat of the earlier calculations. At present, both tasks A and F take longer than the cycle time, thus it would not be possible to operate the line at the faster pace. There are two possible solutions to the problem: a) single tasks could be further broken down and split across work stations in order to be able to balance them against the faster cycle time, or b) two work stations could be charged with the same task and operate in parallel, which overall would give them each twice the cycle time to complete the task. This strategy would lend itself well to task F, whereas the former would lend itself well to task A.

Question 4

a.) i)

- The EPQ model considers two types of cost: holding cost and machine setup cost. The basic assumption of the EPQ model is that – with increasing batch size – the cost of holding inventory increases, as the average inventory equals Q/2. At the same time, the fractional opportunity cost of setting up the machine per item decreases with increasing the batch size Q: the larger the batch, the more fractional productive time can used on the machine. The EPQ model marks the *minimum* of the total cost curve, which is the sum of the holding cost and setup cost. It also assumes a constant annual demand, as well as a steady production rate m.
- Mathematically, the cost curves for one period (year) are:

  Total holding cost = $\frac{1}{2} Q * C_H * (1\text{-}D/m)$
  Total setup cost = $(D / Q) * C_S$

  With D = annual demand, m = production rate, and Q = batch size, C_S = cost for one setup, C_H = cost for holding 1 item in store for 1 year.

  The total cost is therefore: $C_{total} = \frac{1}{2} Q * C_H * (1\text{-}D/m) + (D / Q) * C_S$

  After differentiation, the minimal Q is

  $$EPQ = \text{sqrt}\ [2*D * C_S / C_H * (1\text{-}D/m)],$$

- Annual demand is 3,000 units. EPQ = sqrt [2 * 3,000 * 20 / {(1 * 1.06) * (1-3000/36.500) }] = 1476 portions. This is clearly very high as a result of the low value of C_H

ii) Adding the additional product will have no effect as setup costs for each product is included in the EPQ model.

b.)

- The EPQ model is a derivative of the basic EBQ model, based on the same assumptions. Instead of assuming instant arrival of the batch however, the EPQ formula considers the rate of production in the stock level.

  $$\text{i.e. } EPQ = EBQ * 1/ \text{sqrt}\ (1\text{-}D/m) > EBQ$$

- Overall, the EPQ uses lower inventory levels (assuming a production rate of m>0, all other variables being equal), thus overall yields results that favour larger batches than the EBQ, as the penalty for stockholding is less.

c.)

- The minimum inventory in a manufacturing system is described by Little's Law, which states that the minimum pipeline stock is the product of lead-time and throughput rate.
- In this case, the minimum WIP inventory level is N = 22min/60 * (85 / 14) = 2.2 portions. Thus, the inventory can be significantly lowered by 7 items.
- Littles Law is at best a rule of thumb and ignores many factors such as service levels, variability in throughput and lead time and disruptions.

Question 5

(a)

From material presented in lectures, students should recognise that this question refers to the following issues:

- Process capacity – both theoretical and actual capacity (the two related by the product mix, process time variability and setup times)
- Factory efficiency – whether the different processes in the factory lead to a balanced system
- Process flexibility – the range of products that can be made by the technology within the factory.

In addition, the challenge for automated technology in achieving short life cycle, high variety production includes the complexity of setup (programming) for a new product; physical limits on flexibility – degrees of freedom, size etc.; the robustness of the technology; the difficulty of automating assembly; capital cost of new equipment.
So, the use of process technology to produce several generations of products or more than one product influences capacity planning because:

- Process technology capable of producing many products must be flexible. This is likely to lead to lower theoretical capacity than dedicated equipment, as flexible processes are often slower, and the need for switching between different products implies a requirement for more setup time.
- As more flexibility is required of the technology, the system robustness will generally decline, due to higher chances of an error occurring – which will also lead to higher required capacity.
- Actual capacity will also be reduced, as a line that would be balanced for one product is unlikely to be equally balanced for a different product

The factory design will also be influenced because:

- Line balancing is likely to require an excess of capacity in the flexible machines – to cope with variations in demand, scheduling conflicts and variable process times between products.
- The factory will require workers with skills to setup and maintain flexible machines – rather than manual workers. This will generally involve higher wages per person, so must be evaluated relative to the capital cost of the machines and the potential reduction in the number of people employed.
- The type of flexible technology deployed will depend on the range of products envisaged – generally machines capable of producing greater variety are more expensive, so the factory must be designed with a particular range of future product designs in mind. This may be difficult if the product design moves rapidly driven by technology.
- Generally, flexible technologies are likely to be much less flexible than manual systems – so they are most applicable when the product range can be predicted with high confidence.

(b)

(i) Assume that the output of 50 products per day is consistent, and largely unaffected by the nature of the order. Then the following possibilities exist:
- If all existing work was stopped, the order could be produced in 1 day.
- If the new order 'jumped the queue' of waiting orders, without disturbing the WIP, it would be ready in 11 days.
- If the new order was placed at the end of the existing queue of orders, it would be completed in 21 days.

Thus the delivery date offered could be anything between 1 and 50 days

(ii) The choice depends on how important this customer is relative to the customers whose orders are already in process, or in the queue. If existing orders are from low priority customers, or from customers who are not sensitive to delivery date, or are being made ahead of schedule, or even are being made for stock, it is more likely that the order could be made sooner – particularly if it was a first order from a new customer with potential to place significant business later on. However, if the existing orders are for well established customers with tight delivery lead times, they should not be disrupted. Indeed, if the new order is from a low priority customer, a delivery date longer than 21 days should be selected in order to allow 'buffer' space for any higher priority orders arriving in the next 21 days.

The question illustrates a significant difficulty with order planning systems – as it is difficult to quantify the likely future value of a particular customer order, so the decision is strongly dependent on the sales person's intuitive understanding of the relative importance of orders.

(c) An MRP system typically has higher WIP and longer lead times than a JIT system, where the JIT system generally produces a narrower range of products and has the expectation of a smoother demand.

Generally

JIT: demand management (control of price, delivery date, discounts, forward booking and so on) should be used to aim at constant demand on the production system.

MRP: greater ability to cope with variety in order volumes, particularly in coping with time variation of order volumes between different products. In this case, demand management is required to manage the overall load of the factory, and has much greater flexibility – particularly if the factory has the opportunity to make standard items for stock to absorb what would otherwise be idle time.

Hence for this situation the role of demand management

JIT system, demand management is more likely to be used to meet the needs of the production system for level demand.

MRP system, demand management can be used to balance customer requirements against business requirements – and there is less incentive to drop prices to ensure factory capacity is not left idle.

The question illustrates an important reason why MRP systems remain so prevalent, despite the attractions of JIT: MRP is much better able to cope with product and order variability and can be adjusted more rapidly to respond to market needs.

(TURN OVER)

Question 6

(a) (i) The manager should add capacity before demand has increased if:

- Demand is forecast to grow and past experience shows that forecasts of demand growth are tolerably accurate
- The time required to add capacity is sufficiently long that failure to do so will lead to a competitive disadvantage
- The cost of investment in additional capacity is relatively low compared to the benefit of additional sales
- Delivery time is a key order winner.

(a) (ii) The manager should wait to add capacity until after demand has increased if:

- Delivery time is not a key order winner and customers would rather wait to buy from this supplier than switch to another with shorter lead times (this occurs for products with some degree of monopoly – for instance of luxury or features)
- The cost of adding capacity is too great to justify the investment until firm orders are placed (this is the case with very expensive goods, such as aeroplane or ship production)
- Capacity can be added rapidly, so that all risk can be eliminated from the investment decision. This is crucial in start-up or relatively young businesses, where cash flow is critical, so production should be designed so that capacity can be increased or decreased rapidly, to track market design. It is a major driver of out-sourcing and the use of contracted-out manufacturing.

(b) (i) The unit cost of a product is often lower in a large factory than a small one because

- The cost of capacity is not a linear function of output volume. This is reflected in the idea of the 'economies of scale' whereby the fixed costs of investment spread over the volume of production become proportionately less significant as overall volumes increase.
- As well as capital costs of equipment, some management overheads create economies of scale – where there is a minimum efficient size of marketing group or management team required to allow production at all.
- High indirect costs – for instance in research and development – must be offset by high production volumes. This is the case in pharmaceutical production, where the bulk of costs are in R&D – so the cost are not proportional to sales volume.
- Sales volumes typically become more predictable when more products and more demand is aggregated: sales of one particular product may vary rapidly, where sales for the range of products within a sector are likely to be more predictable. (Clothing is a good example of this.)

Thus a larger factory, having a wider range of products, will see more steady average demand, so can expect to achieve better average capacity utilisation than a smaller one.

(b) (ii) The unit cost of a product may be lower in a small factory than a large one when:

- The capital costs of production are high, but the large factory is failing to attract sufficient orders to use its available capacity – so has proportionately higher overheads.
- Customer demand for high variety and small batches acts to make large scale processes unattractive due to their large setup times and switchover costs. The rise of 'mini-mills' in steel production occurred for this reason – car makers needed only a limited range of steels, and it was cheaper to produce them in dedicated factories than in large integrated facilities.
- The physical process of production shows a diseconomy of scale – many chemical processes show this, and since the massive investment in the Middlesborough plant of ICI, UK chemical plants have generally become smaller, and are still decreasing in size – down to chip size micro-fluidic reactors
- The cost of distribution is high compared to the cost of production: dry-cleaning is a relatively localised business as the cost of bringing material to a central facility would be prohibitive, and increasingly oxygen is made in small scale dedicated plants rather than centrally.
- The product is sold as part of a service package, where the service requires face-to-face contact and shows no economy of scale.

(c) (i) The effect of an unexpected machine breakdown in an MRP system will be that:

- The master schedule cannot be met, as processing times (and queuing times) were assumed constant when the schedule was designed, and typically MRP has no feedback of actual process and queue times. Thus the short term consequence is that all orders will be disrupted and the disturbance will quickly propagate to other workstations, as they are starved or flooded with work.
- However, once the interruption has been identified, the MRP system will be able to reschedule work using other machines – assuming that a substitute process is available.
- The breakdown will not immediately be visible to the manager in the MRP system, as most workstations will have a queue of incoming work, and other workstations will continue to feed new work to the broken station until a general halt is caused. The workers at other stations are unlikely to be motivated to help resolve the situation – and may expect the problem to be solved by a specialist engineering team.

(c) (ii) The effect of an unexpected machine breakdown in a JIT/Toyota system will be that:

- The entire line (upstream of the breakdown) will stop within one cycle (or a small number of cycles, if a small amount of buffer stock has been introduced to help cope with uncertainties.)

- The workers at the affected workstation and nearby will be motivated and trained to attempt to solve the problem, and will have a well defined means to bring other support services in to assist if required.
- Generally the problem should be resolved rapidly, and there will be no build up of unexpected WIP. However, if the problem is long term, the JIT system will be affected badly as it is unlikely to have excess capacity or the ability to re-route work to other similar stations.

Question 7

a)

(i) Four options:

- Direct shipping
- Warehousing
- Cross docking
    - Items distributed continuously from suppliers through warehouses to customers
    - Warehouse rarely keeps items for more than 10-15 hours
    - Requires
    - Close linkage between all participants in supply chain
    - Fast transportation
    - Large distribution volumes
- Transhipment
    - Shipment of items between facilities at same level of supply chain

ISSUE	*Direct shipment*	*Cross docking*	*Inventory at warehouses*
Risk pooling	Neutral	Neutral	Take advantage
Transportation costs	High	Reduced inbound costs	Reduced inbound costs
Handling costs	No warehouse costs	No holding costs	High
Allocation	Neutral	Delayed	Delayed
Disruption Management	Fragile	Fragile	Good

(ii) Numerous examples from industrial visits may be drawn on.

b)

it is immediately possible to determine projected on hand inventory in each case, where

Projected on-hand inventory for any period =
on-hand inventory in previous period +
scheduled receipts in current period+
planned order releases due to arrive in that period – demand in that period

e.g. Warehouse A Period 2 - POI = 110+0+0-80 = 30
Warehouse A period 3 - POI =30+0+100-120=10

Hence:

	Period					
Warehouse A	0	1	2	3	4	5
Demand			80	120	70	120
Scheduled receipts		100				
Projected on-hand inventory	10	110	30	10	40	20
Planned order release			100	100	100	

	Period					
Warehouse B	0	1	2	3	4	5
Demand			60	140	40	100
Scheduled receipts		120				
Projected on-hand inventory	20	140	80	60	20	40
Planned order release		120		120		

And from this data summing to determine weekly factory gross requirements:

Factory

Gross requirements 120 100 220 100

(ii) the factory might a) build up suitable level of finished goods stocks, flexibly schedule its workforce, outsource excess capacity. Note also that planned orders need to be released 1 lead time in advance of their being needed to avoid a stockout. With safety stock a stockout occurs if inventory falls below the safety level. Because the supply process is *internal* it does not makes sense in this context to consider valriable pricing schemes.

Question 8

a)

(i) Causes of the bullwhip effect

- Long cycle times (information/delivery lags)
- Decisions made locally (by one business) not globally (by the whole chain)
- Conservative decision making
  - managers are generally risk averse
  - risks are usually not symmetric - stockout hurts more than excess
- Poor forecasting of demand
- Inflated orders
  - due to wrong incentives
  - due to fear of shortage
- Promotions
- Order batching

(ii) Supply Chain Operations Reference Model (SCOR) Level 1 metrics

- Supply chain reliability
  - % on time delivery
  - Order fulfilment lead time (days)
- Flexibility and responsiveness
  - Supply chain response time (days)
- Expenses
  - Supply chain management cost (%)
  - % value added per employee (£)
- Assets/utilisation
  - Total inventory days of supply
  - Net asset turns

(iii) Tradeoffs are as follows:

Lot size vs inventory levels
  Manufacturer would like large lot sizes to reduce set up costs
  Trend is towards small lot sizes and low inventories
Inventory levels vs transportation costs
  Supplier wants full truckloads
  But may hold inventory for longer to get big enough delivery
Lead-time vs transportation costs
  Short lead times usually mean more, smaller deliveries
Product variety vs inventory levels
  High variety means smaller lot sizes, more (smaller) shipments, higher inventory
Cost vs customer service

b) calculations are as follows:

Average aggregate inventory value= ∑average number of units of each item on hand * value of items
Weeks of supply = Average aggregate inventory value / weekly sales at cost
Inventory turnover = Annual sales (at cost) / Average aggregate inventory value

 (TURN OVER)

Using the data provided:

		Average level	Unit price	value of inventory
Raw materials	R1	2000	0.2	400
	R2	1400	3	4200
	R3	800	5	4000
	R4	700	25	17500
	R5	200	80	16000
WiP	W1	200	250	50000
	W2	120	400	48000
FG	F1	80	1000	80000
	F2	20	2400	48000
				268100

Weeks of supply	Inventory turns
7.45	6.71

i.e.

Average aggregate inventory value= ∑average number of units of each item on hand * value of items
= 268100
Weeks of supply = Average aggregate inventory value / weekly sales at cost
=268100/(1800000/50)
Inventory turnover = Annual sales (at cost) / Average aggregate inventory value
=1800000/268100

(ii) These measures clearly only provide one dimension of supply chain performance relating to costs associated with stock holding and indirectly relating to performance via stock turns.

A good answer here will refer to a) part (ii) and indicate why the other measures are required, providing examples/illustrations.

END OF SAMPLE SOLUTIONS