Manufacturing Engineering Tripos 2011

METII Paper 1

1. Q

(a) Describe the essential features of the following four processes for joining sheet materials: polymer-based adhesive bonding; laser welding; electron beam welding; friction stir welding. [30%]

(b) Discuss the factors which would influence the choice of joining process, from the four listed in part (a), for each of the following applications. For each case suggest, with a reasoned explanation, which of the four would be most appropriate.

(i) Joining textile sheets based on polypropylene, in a high-volume application.

(ii) Joining a 5 mm thick sheet of 2000 series aluminium to a 5 mm thick sheet of magnesium alloy for aerospace application.

(iii) Making tailored blanks for automotive body shells. [40%]

(c) Define the term *micro-manufacturing*. Describe a process which could be used to make a large number of identical components consisting of stainless steel sheet, 50 µm thick, perforated with a complex pattern of holes 500 µm square. Which, if any, of the processes listed in part (a) might be used to join these components, and why would the other processes be unsuitable? [30%]

A

(a) adhesive bonding – uses thermosetting resin which is usually mixed from 2-part components (resin + initiator) and applied evenly (manual brush, spray, extrusion, roller etc) to achieve a thin even film on components and then the joint made and pressure applied (clamping/jig) while adhesive cures. Curing may be at ambient temperature or require moderate temperature rise (oven, electrical heating elements). Surface preparation (cleaning, correct roughness) is vital to a strong bond.

Laser welding – uses laser (infra-red, wavelength typically 1 – 10 µm) as source of heat, usually focused by lens or mirror system and steered/manipulated by movement of beam (mirrors or robotic if fibre laser) and/or movement of workpiece. Rapid heating fuses material to form local weld pool at joint region. Important to control power input, traverse speed to avoid perforation of sheet material. Welding may involve sequence of spot welds or continuous seam weld.

EB welding – uses intense beam of free electrons as energy source. Workpiece must be electrical conductor. Capable of very high penetration depths (irrelevant for sheet welding) but requires vacuum or low pressure chamber and has high equipment cost.

Friction stir welding – uses rotating pin-shaped tool moving along joint line leading to local heating and extensive plastic deformation and intermixing (but no melting). Can bond sheet metals with thickness from 0.5 to 30 mm. Can bond dissimilar alloys with quite different melting points (e.g. Al to Mg).

(b)

Answers should include reference to the following factors:

The mechanical properties required in the article;

the nature of the materials to be joined;

any influence of accuracy levels in assembly and in the final article;

the expected operating environment of the finished article;

production volumes;

process costs;

environmental effects

(i) polypropylene textiles (thermoplastic) – need to avoid extensive melting, and minimal force applied to workpiece during welding. Polpypropylene, like other polyolefins (eg polyethylene) is very tricky to bond adhesively – resins do not wet the low energy surface. Wettability and hence bondability of some polymers can be enhanced by surface treatment (e.g. corona or flame) but for this application the best method would be laser welding, with a thin weld line. In the 'Clearweld' process (TWI) the laser beam is focused at the interface between the two polymer layers and causes local melting, with absorption enhanced in some cases by application of absorbing pigment/dye. Neither EB nor FSW suitable.

(ii) These two dissimilar metals cannot be bonded satisfactorily by fusion processes such as laser or EB (especially as 2000 series Al alloys are heat-treatable and there would be significant loss of strength due to the heating cycle), but the dimensions and material are ideal for friction stir welding. This could achieve a high-strength butt joint. If a lap joint is permissible then adhesive bonding would be a candidate, with attention paid to surface preparation (which may include anodizing of these two alloys). Points for consideration in choosing between these two would include service conditions (stress level, environment – humidity, temperature) and extensive tests might be required to select the process and its parameters.

(iii) tailored blanks are steel sheets composed of (usually) two different steels with a butt joint which are then further processed by pressing to produce automotive body parts (e.g. door panels). They require extremely good bond strength and integrity to surviuve the forming process and are very thin (typically 0.8 mm thick). Low distortion over large dimensions and a thin weld line are required, and laser welding would be suitable. Lasers can also be used to cut and trim the blanks, and the process can be highly automated. EB welding would not be suitable due to the need for large process chambers and long cycle times.

(c) There is no single agreed definition of micromanufacturing, but two are 'the production of parts with functional features or at least one dimension on the order of μm' or 'the production of high-precision 3-D products with feature sizes down to tens of μm'.

For production of the parts from stainless steel sheet, we need a process to produce large numbers of components with a pattern of small holes. The only suitable process discussed in the course was photochemical machining (PCM). Photoelectroforming cannot used for stainless steel (it cannot be electroplated), and processes such as micromachining, LIGA or EDM are too slow for volume production. PCM involves deposition of a thin coating of photosensitive polymer (photo-resist) on the stainless steel sheet, exposure of this coating to UV light through a patterned mask which defines the areas to be removed to create the holes, development of the resist to remove exposed regions (or unexposed regions – depends whether it is a positive or negative process), etching of the steel to perforate the unmasked regions, and stripping of the residual mask. The method is ideally suited to rapid production of large numbers of identical components.

The sheet is very thin (50 μm) and so friction stir welding could not be used (mechanical distortion would destroy the foil). Adhesive bonding would require extreme precision in the application of the adhesive and great care in handling – it is conceivable for certain types of joint and if a low viscosity adhesive is used so that a very thin glue layer is achieved. EB welding is usually much larger scale – perhaps a microbe process could be developed, but it would be very specialised. A very small spot size would be needed. Laser welding could achieve the necessary small spot size and precision, and would be feasible.

2. Q

(a) Outline the processes used to manufacture ceramic and metallic components from powders. Discuss the similarities and differences between the processes for these two classes of materials. What features of the powder route make it attractive for certain types of product, and what are the limitations of this method of manufacture? [30%]

(b) Explain how the properties of conventional powder metallurgy (PM) products differ from products machined from solid bar, and describe two methods by which the properties of a PM component can be improved by additional processing steps. For each method, give an example of a product for which it would be appropriate, and indicate the advantages of this method over machining from solid. [35%]

(c) Explain why careful control of particle size is particularly important in the processing of ceramics via a powder route. Describe two examples of applications for which the use of ceramic components offers significant advantages over the use of metals. In each case explain why the ceramic component is preferable. What obstacles are there to the wider use of ceramic materials in engineering applications? [35%]

A

(a) The process involves blending of metal or ceramic powder with additives (e.g. sintering aids, lubricants, alloying elements), filling and pressing of powder into shaped die, removal of 'green' compact from die, (possibly green machining to produce features not present after pressing), sintering at high T to bond particles, and cooling (may be combined with quenching to achieve correct mechanical properties. The processes for ceramics and metals are very similar except that deformation of metal particles occurs during pressing so that high densities are achieved which then change very little during sintering. For ceramics, there is substantial porosity in the green compact (perhaps 50% volume) which then reduces during sintering so that the part shrinks (10-20% linearly). Sintering temperatures are $>0.7T_m$ so higher temperatures are generally needed for ceramics. Powder routes are net-shape, capable of relatively high precision and can produce materials with low (but not zero) porosity and good mechanical properties. Parts may require minimal finishing after sintering. High costs of die/punch tooling mean that the method is suitable only for large production volumes (> 10,000), and limitations on press size mean that part size is limited (typically < 1kg for steel and often much smaller).

(b)

PM products generally have some residual porosity which reduces tensile strength, elastic modulus and toughness compared with wrought bar. Additional process steps which can be applied are sinter forging and surface rolling. Sinter forging involves production of a sintered compact which is then hot forged (with closed dies) to achieve final shape and also consolidate to reduce porosity to zero. This is successfully applied to automotive engine con-rods (steel) and to transmission components (synchroniser rings). Surface rolling (cold) can be applied to sintered steel gears to consolidate and work-harden surface regions and achieve high strength and toughness in gear teeth – successfully applied to automotive gears. (HIP can also be used – not covered in the lectures but involves application of high isostatic pressure by gas – argon – to increase density and improve properties to wrought values). In all these examples there are significant savings in reduction of process cost, scrap production and ability to produce complex shapes which would involve lengthy machining cycles. Sinter forging of con-rods allows introduction of controlled sharp notches for fracture splitting (which could not be done by machining) and rolling of gear provides local work-hardening which gives advantages in mechanical properties over tooth cutting by hobbing etc.

(c) Particle size in ceramics controls the maximum flaw size in a sintered component, and thus in a brittle material determines the fracture strength. Maximum flaw size is also dependent on sintering conditions and composition. Some applications where ceramics have advantages over metals include: cutting/slitting blades for polymer film; tools for metal tube rolling; cutting tools; extrusion dies for copper and brass; pump components. In all these ceramics offer lower wear rate, greater precision (because of greater stiffness and shape/edge retention), longer life, less downtime for replacement and adjustment, lower overall cost. Obstacles to greater use of ceramics in engineering applications include: high initial cost, compounded by low production volumes with no economies of scale; lack of appreciation/comparison of true lifecycle costs for different materials; lack of national/international specifications and standards for ceramic materials so that much depends on quality of individual supplier; for some applications, lack of toughness; ignorance among designers and engineers of properties and opportunities.

3. Q

(a) Describe the range of configuration options that exists for automating assembly of manufactured products. [50%]

(b) Discuss the factors that you would consider when making a choice of appropriate assembly method, whether manual or automated. [50%]

A

(a) The range of configuration options for automating assembly covers:

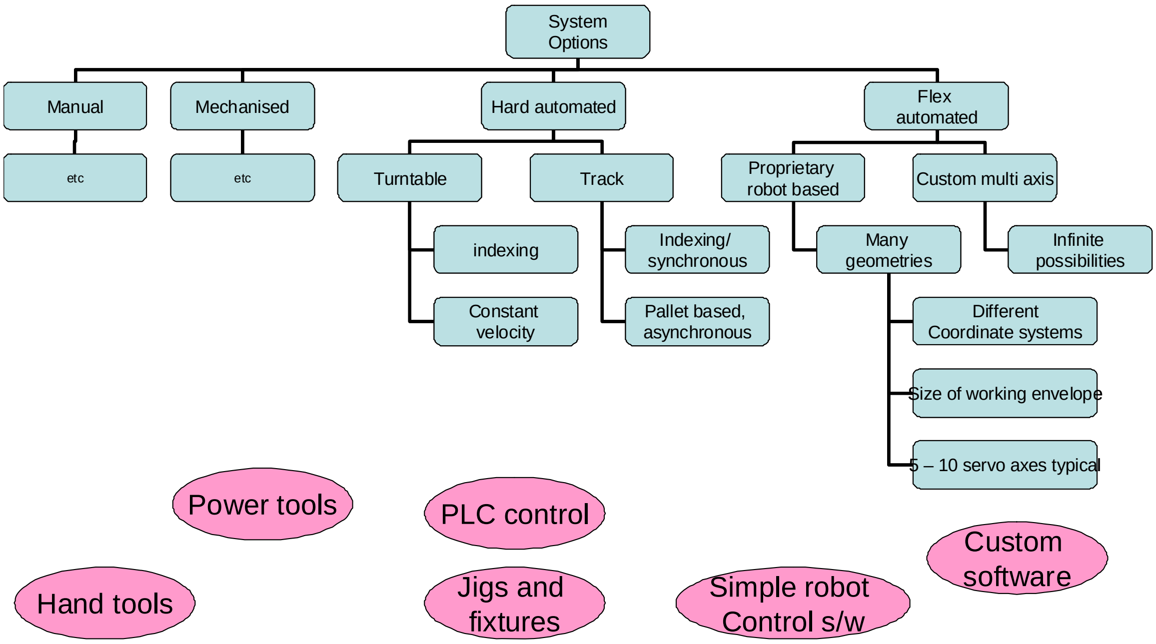
- mechanised methods, in which machines help people to do the job
- hard automation, in which machines do the same job every cycle
- flexible automation, in which robots and other software-driven machines do the job, which can be different each cycle

Solely manual methods are not considered as these are not part of an automated solution.

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 hard automation and flexible automation options can be further decomposed and described as shown in the following diagram:

Assembly options:Tools and skills required



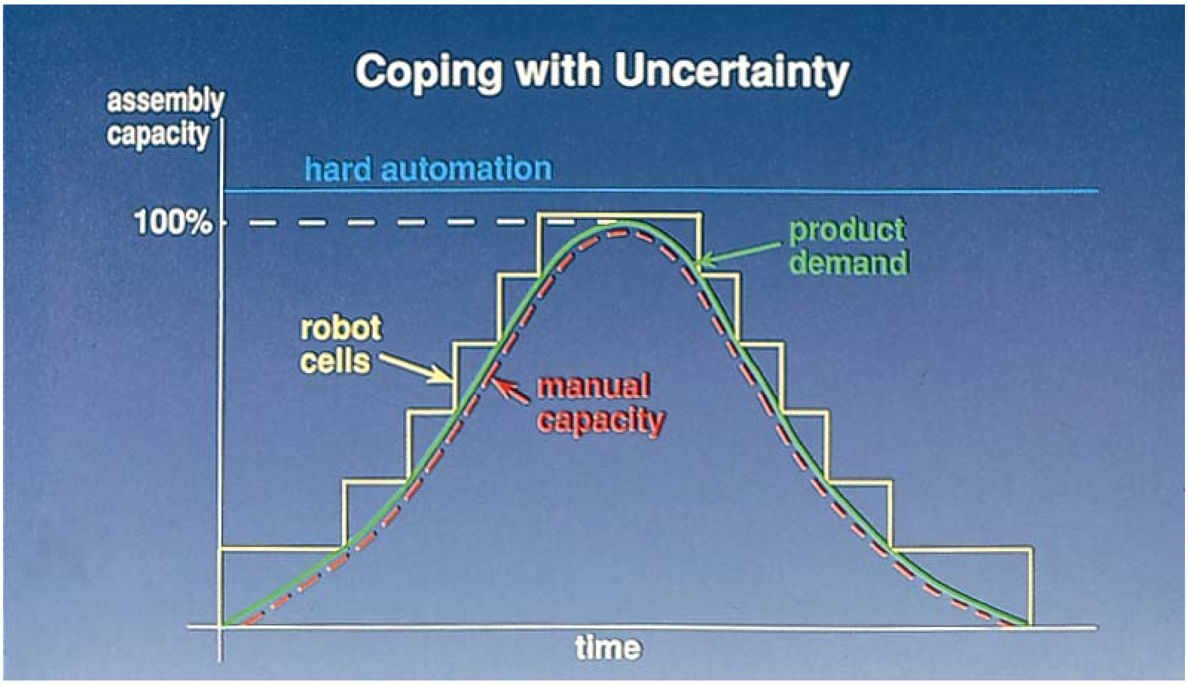
(b) Discuss the factors that you would consider when making a choice of appropriate assembly method, whether manual or automated.

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. Each quadrant has its own distinctive characteristics in terms of manufacturing system requirements.

Factors to take into account 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, 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.



4. Q

a) Discuss the features that need to be considered in the design of:

i) a robot end-effector for handling small sheet metal components;

ii) an assembly fixture for the automatic assembly and riveting of sheet metal components.

For each outline a possible design solution. [40%]

b) Discuss the capabilities of a modern programmable logic controller (plc), explaining in detail the features that make it highly suitable for controlling industrial automation. [25%]

c) Many modern automation control systems are being developed using distributed architectures.

i) Outline the design features of these architectures, and describe in detail the role of RFID as a key enabling technology for such architectures.

ii) Discuss the benefits that can be achieved with these architectures. [35%]

A

a)

End effector needs to cope with different sizes and weights of components, needs to hold component firmly enough to prevent movement during transport, ideally needs to be able to pick up on a flat surface needs to have sensing to detect part presence.

A multi switchable vacuum cup gripper with proximity sensors for part detection would be one solution. Vacuum could be switched to appropriate cups by means of solenoid valves controlled through the robot controller.

Assembly fixture needs to accurately locate components and firmly clamp them while riveting operation occurs. Sensing for part presence is required.

Design solution needs to incorporate kinematic location principles for base part, possibly using pneumatic pistons pushing up to fixed stops with proximity sensors for part detection, and clamping with toggle clamps. Additional parts can be positioned by robot and clamped similarly providing that no great accuracy is required and parts have been prepositioned in a kitting tray. The uses of a kitting tray should be illustrated.
For high accuracy level a dowelling system could be designed, but this requires care to avoid jamming. Cut away dowels, ideally with lead–in taper would be needed.

b)

Typical I/o
Scan rates
Modular design
Expandable by adding modules to do specific task

Features suiting industrial automation:
Deterministic Operation (known and repeatable scan time)
Known fault modes,
Robust design, factory hardened, not subject to electrical noise etc.
Integration to industrial networks (supports most common factory networks making communication easy, network ability allows addressing of I/O obviating need to hard wire)

c) i) The design features of a distributed control systems are:
Overall control system to be implemented as sub control modules, optimised for a specific production elements.
The control module will allow full functionality of a production module. (Customised Operations)
Control modules can be implemented on different hardware platforms and at different locations around the production line. (Fixtures, Conveyors, Robots)
Typically each of the control modules has a common communication interface that allows them to easily communicate to form the overall control system.
Production decisions can be carried out at each of the local production elements.
Radio Frequency Identification (RFID) is a non contact identification technology using RF.
Each production module needs to recognise the component and be able to make a decision about what operations need to be performed. This is best done by the component carrying with it an operation list (with routing) that is updated as operations are performed.
RFID tags that are read/write provide a good mechanism for doing this.

RFID readers can situated at each of the production elements to identify parts as they arrive. The local control module is notified that the part has arrived and it interrogates the data sequence on the RFID tag. The data sequence specifies an operation to be performed and if the production element is free it's carried. Once the operation has been carried out the RFID data associated with the shuttle is updated to show a particular operation has been performed. The RFID data can easily be customised for different production sequence required. This technique can also be used to help schedule parts through the production system; if a particular production element is busy the part / shuttle can be re-circulated around the conveyor until the resource is free. The RFID data can be used to record a priority level due to number of times it has re-circulated around the system or from a specific business demand (Rush Order)

ii)Benefits: Modular design, fast development, ease of de-bugging, ease of modification & customisation of production system, flexibility of operation eg to cope with equipment breakdown.

5. Q

(a) Explain why effective asset management is important to organisations in the oil and gas sector. [25%]

(b) Discuss the different factors related to maintenance that should be considered during plant design. [25%]

(c) Discuss the use of a risk assessment matrix in developing an asset maintenance strategy. [25%]

(d) Explain with examples the factors that can be used to differentiate between good and bad maintenance services. [25%]

A

(a) Effective asset management delivers value to any organisation from the following perspectives:

(i) To increase the reliability – this would translate to less breakdowns, higher productivity, and possibly better quality products, etc.

(ii) To increase the efficiency – improper (or lack of) maintenance may result in degradation in performance, and hence lower output, quality etc.

(iii) To increase the life of the equipment – especially critical in repairable systems – by better maintenance, the design-life of the equipment can be extended. This can also be done by upgrading various components/sub-systems selectively.

(iv) To comply with regulations – this is important for safety-critical operations such as petro-chemical industries, and also for other industries

(v) The "shine" factor – poor maintenance = poor quality = bad customer perception

[Good responses will discuss each of the factors from the perspective of the O&G sector].

(b) The different factors related to maintenance that must be considered during product design are:

- Sparing/redundancy

  Assess as cost of extra facilities vs value of production

  Sometimes more difficult, e.g:

  Environment Agency expects you to move from oil to gas firing on steam boilers.

  Single vapouriser train costs $3M and achieves 99.9% reliability.

  Is it worth installing a second facility?

- Material Selection

  Assess repair / replace frequency and cost of spares vs material costs.

- Maintainability

  Equipment layout, spacing, number of isolation valves etc.

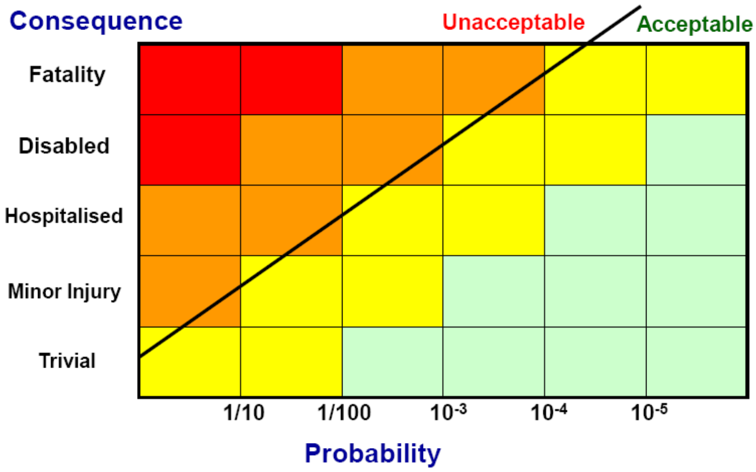
- Installation of monitoring systems.

  Particularly those that are costly to retrofit.

- Unusual equipment

  Impact on standardisation of spares, workforce skills needed to maintain the equipment.

(c) When developing a maintenance strategy, in most cases, we are not dealing with an absolute ("no failure"), but managing the risk of loss of performance vs the cost of maintenance. There are various types of risks involved in a maintenance decision. Examples of the different types of risks (of not maintaining properly) are: equipment downtime, failures that can cause safety issues, degradation of product quality, hiding other potential failures, etc. If we consider these are different possible outcomes of failure, risk is quantitatively calculated as the product of the probability of an outcome and the consequence of the outcome. The consequence can be quantified either on a monetary basis or on any scale suitable to the situation.



In most industries, a "risk matrix" is used to determine the risk profile of an asset – which is then used to determine the appropriate level of attention and action to be attributed to the asset. An example of a risk matrix used in the petrochemical industry is shown in figure above. Here, the safety risk involved in the failure of an equipment is assessed. The consequence of the failure is measured in terms of varying degrees of injury to the operator. After determining the risk profile of the asset, the organisation has to decide the amount of risk that is acceptable. If the risk is deemed to be above acceptable levels, an appropriate maintenance action is taken.

(d) The essence of a good service can be captured by the following elements:

(i) Service experience: customers' direct experience of the service
(ii) Service outcome: the result for the customers of the service
(iii) Service operation: the way in which the service is delivered
(iv) Value of service: benefits and costs the customers perceive from the service

[Good responses will use examples to illustrate each of the elements, highlighting good and bad examples of services]

6. Q

(a) What is an eco-audit? Explain how you would conduct an eco-audit to allow an estimate to be made of the energy payback period of a wind turbine. Discuss the limitations of the eco-audit approach in the wider context of sustainability audits. [60%]

((b) Outline how you would assess the *green credentials* of a factory, using specific examples to illustrate your discussion. [40%]

A

(a) An eco-audit is a tool for assessing the energy consumption over the whole lifecycle of a product. It looks only at energy and does not look at factors such as toxicity of materials. The system boundaries are pre-defined if a system such as CES is used to provide data, but otherwise will need to be considered explicitly. Material production energies, manufacturing process energies and transport are the main factors. In the 'use' phase, a contribution to electricity transmission infrastructure should be included.

To conduct an eco-audit, two sets of input data are required. The user specifies: (a) the breakdown of the product into materials with their respective masses and manufacturing routes; (b) the types of transport used and distances involved in manufacture, installation and maintenance; (c) the duty cycle – energy consumption during use, and (in the context of energy-producing devices) the energy output over the product life. These are combined with data in CES: (i) primary production energy (i.e. per kg of raw material – sometimes referred to as the *embodied energy*); (ii) manufacturing energy (e.g. again per kg of material, for forming, moulding, extrusion etc); (iii) typical transportation energies (per tonne, per kilometre); (iv) energy conversion efficiencies. Energies consumed and potentially recovered in the disposal stage are not currently included. The output is the energy (or CO_2) audit for the first four stages, together with a summary of the input data.

The amount of energy generated by the turbine will be estimated using local wind data to find a *capacity factor* – the fraction of the rated power output that is actually achieved, averaged over the year.

(b) Environmental assessment of a company can involve very different criteria, depending on the purpose of the assessment. It could be prudent to include some mention of 'popular' metrics as well as the more significant environmental factors.

A good place to start is finding whether the company has been convicted of infringements of any standards of emissions (e.g. gaseous emissions or pollution of land or water).

The company website may contain some information, but for any kind of in-depth analysis it will be necessary to visit the site and interview some of the management team, as well as staff from all levels within the company. In a truly 'green' company there should be high environmental awareness throughout.

Assessment could be based on some of the 2010 Sunday Times environmental competition criteria:

- Environment management system (EMS): an EMS that meets the ISO 14001 international standard

- Public reporting of green issues: green credentials subject to third-party verification
- Carbon footprint: companies which have calculated their carbon footprint
- Green training: evidence of environmental awareness in the factory (e.g. avoidance of waste of any resources)
- Electricity, gas and water consumption: signs of continuous improvement
- Waste management: signs of reduction in waste, including reduction in waste sent to landfill.
- Information about the environmental credentials of suppliers to the company and supply chains may be difficult to gain on a casual visit, but positive factors would be use of local suppliers, and a negative factor would be materials and components arriving by air freight from countries which are largely unregulated.

Publicity within a factory often focuses on the role played in the community. Whilst activities such as funding the local school sports day are pure greenwash, there is some value in activities which provide environmental education (e.g. educational factory tours).