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ENGINEERING AND MANUFACTURING

CORE

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1 Working within the engineering and manufacturing sectors

Introduction

Modern life as we know it would be impossible without the efforts of millions of engineers and engineering technicians who apply scientific principles to find practical solutions to real-world problems. They are responsible for designing and manufacturing a staggeringly broad range of products across multiple sectors, from chemical engineering and pharmaceuticals to aviation and space exploration.

This chapter provides an overview of the engineering and manufacturing industry and explores the activities of engineers working in these sectors.

Learning outcomes

By the end of this chapter, you will understand:

1. how different types of manufacturing processes influence the design of engineered products
2. how different requirements affect the user and designs related to the manufacture of products
3. the steps of the linear and iterative design processes, and the contribution that testing makes to achieve a suitable and effective design
4. how to interpret anthropometric data
5. the role and purpose of maintenance, repair and installation
6. the advantages and disadvantages of different approaches to maintenance
7. the responsibilities of the different roles involved in maintenance
8. approaches to monitoring and the reasons for carrying out monitoring
9. the reasons for, and implications of, shutdown and servicing
10. an overview of the types of tools and equipment used
11. the reasons for commissioning activities
12. how effective maintenance reduces impact on the environment, and the safe and environmentally friendly disposal of waste
13. how the scale of manufacture affects the level of automation
14. examples of products made at different scales of manufacture
15. different types of manufacturing infrastructure, their purpose and relative advantages and limitations
16. the purpose and application of CAM systems and software
17. the advantages and limitations of different levels of automation.

1.1 Key principles and methodologies in engineering and manufacturing design

Types of manufacturing process

A wide range of processes are used in the manufacturing industry:

- **Wasting** involves the removal of material from a workpiece to produce a component of the required size and shape. For example, when drilling, the drill bit cuts material away to form a hole. The waste material generated is carried away from the cutting edges in the form of chips or swarf.
- **Forming** uses the application of force to change the shape of a material. For example, using a press tool to bend a length of flat steel bar into an L-shaped bracket.
- **Shaping** involves pouring or injecting liquid material into a mould where it then solidifies into the required shape.
- **Casting** is a shaping process which involves heating a material above its melting point and pouring the resulting liquid into a mould, where it then cools and solidifies into the required shape.
- **Joining** processes are used to fix two or more components together into a larger assembly. Examples include welding, where components are fused together permanently, or the use of nuts and bolts that allow disassembly for maintenance or repair.
- **Finishing** adds a coating to the outer surface of a component that protects it from corrosion. It can also improve aesthetics.
- **Additive manufacturing** describes a range of advanced processes able to create complex components directly from three-dimensional computer models. Often referred to as 3D printing, it involves the direct addition of material, usually in a series of thin layers which are gradually built up into the required shape. This differs from conventional wasting processes, which remove material from a workpiece to create the feature required.

Key terms

Wasting: removal of material from a workpiece to produce a component of the required size and shape.

Forming: application of force to change the shape of a material.

Shaping: pouring or injecting liquid material into a mould where it solidifies into the required shape.

Casting: a shaping process which involves heating a material above its melting point and pouring the resulting liquid into a mould, where it then cools and solidifies into the required shape.

Joining: a process used to fix two or more components together into a larger assembly.

Finishing: adding a coating to the outer surface of a component that protects it from corrosion. It can also improve aesthetics.

Additive manufacturing: creation of complex components using 3D computer models; material is added in a series of thin layers which are gradually built up into the required shape.

▲ Figure 1.1 In sand casting, molten metal is poured into a sand mould

Test yourself

State the type of manufacturing process for each of the following:

- 3D printing
- MIG welding
- drilling.

Research

To speed up the manufacture of prototype components, 3D-printing technologies can be used to produce fully functional parts in metal.

Carry out research on two such technologies:

- direct metal laser sintering (DMLS)
- metal fused filament fabrication (metal FFF).

Summarise your research and present your findings in a report that explains their:

- operating principles
- benefits and limitations.

The influence of manufacturing process on product design

Engineered products and their components are designed to make their manufacture as easy and cost effective as possible. As such, the preferred manufacturing process or processes can have a considerable influence on design.

For example, a company that specialises in welding assemblies from flat steel components will naturally prefer this approach when asked to design a garden bench. In contrast, an iron foundry would be able to produce a far more decorative, flowing design in cast iron.

Often, design features are included that serve no other purpose than making manufacturing easier, or in some cases, making manufacturing even possible. For example, when casting into a reusable mould, it is essential that the component is designed with a slight taper or draft angle. Without this, the component would become stuck in the mould once it cooled and solidified.

On many sheet-metal components, you will find small holes placed along edges or in corners. Often these are hanging holes, which allow the bare metal components to be suspended on hooks for painting or powder coating during manufacture.

The design process

The first step in the design of a new product is for the client to write a **design brief**. This defines the purpose of the product and outlines all the needs that must be met in order for it to be **fit for purpose**. These will include the key **functional requirements** of the product, as well as other important factors, such as its impact on the environment, its aesthetic appeal or its cost.

Key terms

Design brief: a document which defines the purpose of a new product and outlines all the needs that must be met.

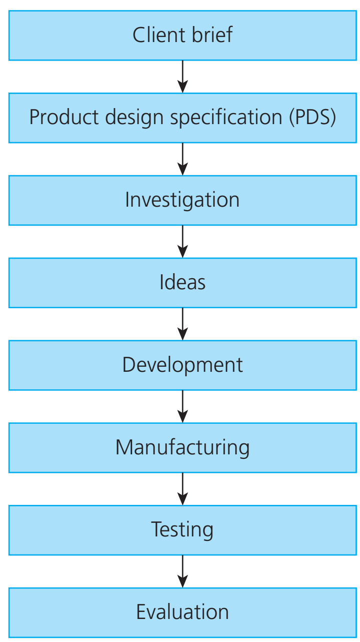
Fit for purpose: where a product fulfils the purpose for which it was designed.

Functional requirements: what a product must be able to do in order to fulfil its basic purpose.

There are several design methodologies that can be used to structure the development of a final design proposal that will meet this brief.

Linear design

A **linear design methodology** follows a series of sequential steps in order to generate a single final design solution.



▲ Figure 1.2 The sequential steps of the linear design process

Key terms

Linear design methodology: a right-first-time approach to the design process, with no structured opportunities to improve the initial design solution.

- Client brief – the client outlines their requirements and all the needs that must be met by the final design solution.

- **Product design specification (PDS)** – design engineers analyse the contents of the client brief and translate each requirement into specific and measurable criteria. This PDS is discussed and agreed with the client, and it describes in detail how designers will fulfil the needs laid out in the client brief. The PDS is used alongside the brief to determine whether the final design proposal is fit for purpose.
- Investigation – design engineers investigate ways of achieving each of the criteria in the PDS. This includes research into materials, processes, existing related products and applicable technologies.
- Ideas – designers generate many ideas to address each requirement of the PDS. This can include the use of thumbnail sketching, brainstorming and other ideation techniques.
- Development – designers take the best elements of the generated ideas and develop these into a design solution that will address the requirements of the PDS. At this stage, materials and processes will be defined and design drawings will be finalised for the completion of the product.
- Manufacturing – the physical product is manufactured.
- Testing – the product is tested to determine whether it fulfils the requirements of the PDS and the client brief. This is the first opportunity to see how a new product works in the real world.
- Evaluation – this is an opportunity at the end of the linear design process for designers to assess how well their solution performed against the requirements of the PDS and the client brief.

Key terms

Product design specification (PDS): a list of specific and measurable criteria that define how a product will meet the requirements of a design brief.

Test yourself

Name all the steps in the linear design process.

The principal weakness of the linear design process is that the first fully developed solution is adopted and used to manufacture the finished product. In practice, it is extremely unlikely that this initial solution will offer optimal performance, and the evaluation stage will uncover weaknesses that could and should be addressed.

Iterative design

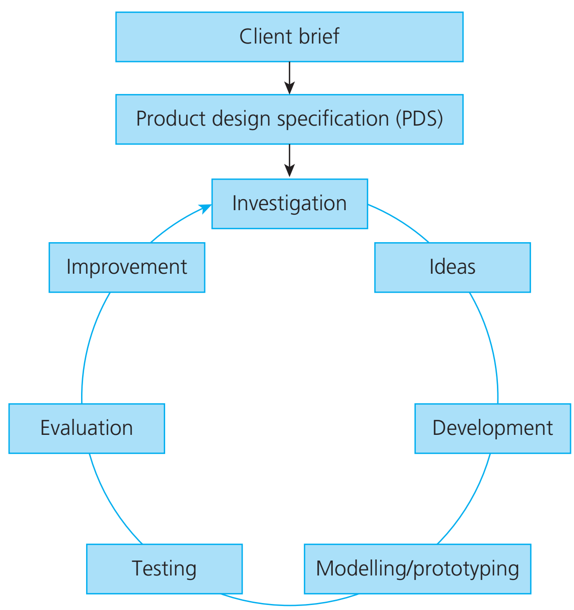
An **iterative design methodology** uses similar steps to linear design but with two significant differences:

- Instead of development leading straight into product manufacture, a model or prototype is made and tested first.
- After testing, the evaluation stage generates suggestions for improvements that will bring the performance of the product closer to the needs identified in the PDS and the client brief.

Key term

Iterative design methodology: an iterative approach to the design process, with structured opportunities to improve the design solution over several design cycles.

The suggested improvements are then fed back into the investigation stage and the process is repeated in order to realise an improved design solution. This iterative cycle is repeated until the final design fulfils all the requirements of the PDS and the client brief, and no further improvement is necessary. This approach enables and encourages a culture of continuous improvement, which ultimately leads to better products and higher sales.



▲ Figure 1.3 The iterative design cycle

Test yourself

Explain the difference between a linear and an iterative design process.

Other approaches to design

There are several other approaches to the design process which emphasise a range of wider social, economic and environmental priorities:

- **Inclusive design** focuses on making design solutions that are accessible to the widest possible proportion of society, including those with physical or mental impairments.
- **Ergonomic design** ensures a product is safe and comfortable to use by taking into consideration both human behaviour and the size, strength and limitations of the body. This includes referring to **anthropometric data**, which provides guidance on typical measurements of different parts of the human body.
- **User-centred design** is an iterative approach that focuses on feedback from the end user of a product during its design and development.
- **Design for manufacture** ensures products incorporate features that support the use of a particular process in their manufacture. For example, the use of draft angles on injection-moulded components allows them to be easily released from the mould tooling during manufacture.
- **Design for assembly** ensures that assemblies can be put together easily, with intuitive positioning and alignment of each individual component. For example, asymmetric mounting holes on symmetrical components so they can only be fitted in the correct orientation, self-jigging features such as slots, and locating holes to allow quick and easy positioning of components.
- **Sustainable design** embeds sustainable principles in the design process to ensure that environmental impact is minimised through reduced use of energy, natural resources and materials.

Key terms

Inclusive design: design approach that focuses on making design solutions that are accessible to the widest possible proportion of society.

Ergonomic design: design approach that ensures a product is safe and comfortable to use by taking into consideration both human behaviour and the size, strength and limitations of the body.

Anthropometric data: research-based data that provides guidance on typical measurements for different parts of the human body.

User-centred design: iterative design approach that focuses on feedback from the end user of a product during its design and development.

Design for manufacture: design approach that ensures products incorporate features that support the use of a particular process in their manufacture.

Design for assembly: design approach that ensures assemblies can be put together easily.

Sustainable design: design approach that ensures environmental impact is minimised through reduced use of energy, natural resources and materials.

▼ Table 1.1 The 6 Rs of sustainable design

Reduce	Reduce the amount of material, energy and waste involved in manufacturing and using a product
Refuse	Refuse to use harmful or polluting materials or processes
Rethink	Rethink conventional, unsustainable approaches, for example the choice of materials or production processes
Repair	Design products that enable straightforward repair and refurbishment in order to extend their useful lives
Reuse	Design products that can be reused and avoid single-use disposable products Repurpose existing components, products or waste materials
Recycle	Use recycled materials and/or ensure materials are recyclable The design should allow easy separation of different material types when the product reaches the end of its useful life

Research

Research is an important way of gathering information that will inform the design of a new product through all stages of its development.

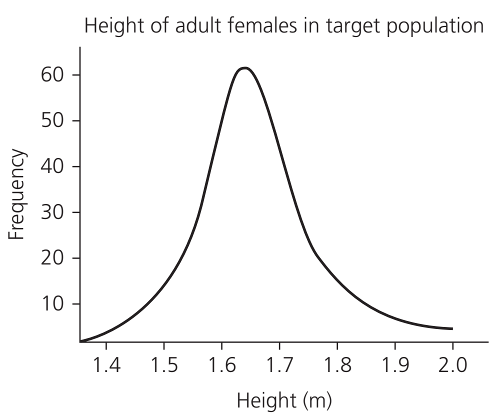
At an early stage, market research is carried out to establish if there is sufficient interest in an idea for a new product to justify its development. The use of interviews and questionnaires can also help to gauge the relative importance of the features and capabilities of the product among potential customers. Useful insights from this process will be incorporated into the client brief.

When a prototype or early production model is available, further market research and user experience testing are used to determine the strengths and weaknesses of the design from the point of view of the end user. Responses can be fed back into the iterative design cycle and used to inform improvements that will make the product more attractive to potential customers. This process might be repeated several times and helps to maximise the commercial success of a new product by ensuring it fulfils the expectations of its target market.

Using anthropometric data

Research on body sizes provides anthropometric data that plays a key role in ergonomic design. It enables designers to understand the different shapes and sizes of the human body, which is vital information for a product which physically interacts with the user.

When summarised in frequency distribution graphs, anthropometric data shows how common specific body measurements are across a population. Anthropometric data is normally distributed, and graphs of measurement versus frequency show the classic bell-shaped curve.



▲ **Figure 1.4 Graph showing frequency distribution**

Clothing manufacturers rely on accurate anthropometric data to determine the size ranges for their products. Each size is designed to accommodate a narrow range of body measurements. The full range of sizes, typically from extra small (XS) to extra large (XL), accommodate the majority of people in the anthropometric data distribution.

The population at the smallest and largest extremes of the data distribution are usually outside the range of standard sizes supplied by manufacturers. The demand for sizes smaller than XS or larger than XL is low, so it may not be commercially viable to manufacture clothes in these sizes.

Other products, such as chairs, adopt a one-size-fits-all approach. Here, the shape, strength and height of the product are designed to accommodate a wide range of body shapes, sizes and weights. For example, if we consider the design of a chair, then it is reasonable to make it strong enough to accommodate bodyweight at the 99th percentile of the anthropometric data distribution. That way, 99 per cent of the population will be able to use it and the number of potential customers will be maximised. If the chair was designed to accommodate bodyweight at the 50th percentile, or median, then it would be less expensive to make but only half of the population could safely use it.

Test yourself

Explain how anthropometric data might be used in the design of an office desk.

Testing

Testing is a vital part of the design process and ensures that design solutions are suitable, effective and safe.

Tests are designed to check that each element of the client brief and the PDS has been fulfilled. They are conducted using a range of methodologies:

- Functional testing confirms that each of the functional requirements of the product is fulfilled. This ensures that the product's main purpose is achieved and that it can perform the actions it was designed to complete. Functional tests are performed by engineers who are comfortable with the technical aspects of the design and who are able to conduct complex testing and interpret the results.
- User-experience testing is based on field tests, where products are used in their normal working environment by real end users. This provides feedback on more human-focused reactions to a product: whether it is attractive, comfortable, useful, intuitive to operate, and whether it lives up to the expectations of the user. Users are generally non-technical, with little or no knowledge of the technical aspects of the design. As such, the tests they are required to complete must be explained clearly and any questions they are asked must avoid using jargon or complex technical terms.
- Safety testing is an essential part of product design and manufacture. The tests range from basic visual checks for sharp edges on individual components to full destructive crash tests on new car designs.

- Compliance testing ensures that a product complies with any applicable safety or quality assurance standards that might be required for a product to be sold in a particular market. For example, CE marking is used to indicate goods sold in the European Economic Area (EEA) that have been tested and comply with basic safety standards.

Communicating with different audiences

Market research, testing and other design activities require input from both technical and non-technical audiences. Different approaches must be taken when communicating with these two groups.

For example, technical audiences are likely to be interested in exactly how certain aspects of a complex product, for example a mobile phone or wireless earbuds, function in granular detail. They will want to drill down into performance data and technical specifications, and will be able to interpret technical language.

In contrast, most end users of complex products will have little or no insight into the technical aspects of how these products work. However, they still need to be engaged in order to provide essential feedback on how a product looks, feels and operates in real-world conditions. For non-technical audiences, complex information needs to be summarised and simplified. Often this information is made more visually engaging by expressing it graphically using images, charts or diagrams. Where explanatory text is needed, this should be written in plain language without the use of jargon or complex technical terms.

Test yourself

Name two things that should be avoided when communicating with non-technical audiences.

1.2 The role of maintenance, repair and installation in engineering

Installation and commissioning

Before new equipment arrives on site, preparations must be made by the local maintenance team to ensure that:

- Any disruption to the normal running of the factory is minimised.
- Access is large enough for the equipment to enter the factory.
- The site for the equipment is large enough and the floor is strong enough to support it.
- **Provision of services** has been organised and prepared for connection to the new equipment.

Installation is usually completed by specialist teams trained by the equipment manufacturer. This ensures that the equipment is transported, positioned, mounted, assembled and connected to services safely, efficiently and according to the manufacturer's recommendations.

Following installation, the equipment is commissioned. **Commissioning** is the process of getting everything up and running, and training staff to use and maintain the equipment safely and effectively. This will help to prevent accidents, minimise breakdowns and extend the service life of the equipment.

Once everything is operating smoothly and the client is satisfied with the performance of the equipment, they will sign off the installation and accept responsibility for the equipment from the installers.

Key terms

Provision of services: supply and connection of electricity, gas, ventilation, compressed air or water to equipment or machinery.

Commissioning: process of getting a newly installed machine or piece of equipment up and running, ready for handover to the customer.

Health and safety

An important aspect of installing and commissioning a new piece of equipment is to review and update the relevant health and safety risk assessments to ensure that any new hazards or increased risks are managed effectively.

Maintenance

Maintenance encompasses all the activities involved in the installation, commissioning and ongoing care of machines and equipment that ensure they are kept in good working order.

Effective maintenance:

- maximises the service life of machinery and equipment so that it lasts longer and needs to be replaced less frequently

- minimises downtime caused by unplanned breakdowns, thereby avoiding costly delays in production
- ensures equipment runs correctly and efficiently
- reduces impact on the environment by ensuring waste materials are managed safely and disposed of responsibly.

Test yourself

Explain the importance of effective maintenance.

Types of maintenance

Planning maintenance activities is essential in order to minimise equipment downtime and any disruption that this may cause. Ways of organising ongoing planned maintenance include:

- **reactive maintenance**
- **preventative maintenance**
- **condition-based maintenance**.

Key terms

Reactive maintenance: maintenance carried out when there is an equipment failure.

Preventative maintenance: maintenance that uses manufacturer-recommended fixed service schedules to regularly repair or replace components prone to wear, before they fail.

Condition-based maintenance: maintenance enabled by modern sensor and communication technology that allows real-time monitoring of the condition of complex equipment.

Reactive maintenance

Reactive maintenance is carried out when there is an equipment failure. This requires contingency planning to ensure that equipment can be replaced or repaired as quickly as possible when it fails. This makes sense in situations where replacement or repair is fast, simple and inexpensive. For example, when drilling holes, drill bits occasionally break. Having a stock of drill bits on hand and quickly replacing the broken bit is an example of reactive maintenance.

Preventative maintenance

Preventative maintenance is generally used on large complex systems with many moving parts. It uses manufacturer-recommended fixed service schedules to regularly repair or replace components that are prone to wear, before they fail. It also ensures that consumable items, such as lubricants or filters, are replaced regularly. This minimises the likelihood of serious equipment failure and any associated unscheduled downtime required to carry out repairs.

For example, trains are complex systems that include dozens of mechanical and electrical systems. Train breakdowns can cause massive disruption to rail services and so must be avoided. In this case, it is cost effective and convenient to schedule regular preventative maintenance tasks to be carried out quickly in specialist facilities, rather than deal with an increase in in-service breakdowns.

Condition-based maintenance

Condition-based maintenance is enabled by modern sensor and communication technology that allows real-time monitoring of the condition of complex equipment. Data on vibration, temperature and operating conditions is recorded and monitored over time. Analysis of this data can indicate exactly when servicing or component replacement is required. This means that parts in good working order, and which show no signs of wear, are not replaced, which they may have been as a matter of routine in basic preventative maintenance schedules. It also means that parts that have worn prematurely between scheduled maintenance cycles are identified and replaced.

For example, Rolls Royce monitors real-time data from its jet engines in flight around the world. Analysis of this data is used to identify early signs of potential problems and indicates when maintenance procedures need to be carried out on specific engines. This approach minimises any chance of engine failure and increases the efficiency and effectiveness of maintenance activities.

Test yourself

Explain the difference between reactive and preventative maintenance.

Maintenance operations

Maintenance operations are practical actions carried out by maintenance staff and machine operators to keep equipment and machinery in good working condition. They include the following:

- Monitoring the condition of equipment and machinery: this can be as simple as the operator performing a basic visual inspection of their machine at the start of each shift. More complex monitoring strategies involve using sensors to monitor and record key operating characteristics, such as temperature, vibration or oil pressure. Any change in these might be indicative of an emerging problem that warrants investigation.
- Shutdown: this involves taking a machine or piece of equipment out of service so that it can be worked on. It is more than just switching it off. To ensure the safety of maintenance engineers, all the services connected to the equipment must be isolated and locked off, including electricity, gas, water or compressed air. Next, any stored energy in the equipment itself must be released. This ensures that everything is completely de-energised and can be dismantled and worked on safely.
- Servicing: this is usually a scheduled set of procedures required to care for a machine and keep it in good working order. It can include replacing consumable items like filters, topping up fluid levels and lubricating working parts.
- Repair: this is often an unplanned response to a breakdown that requires the replacement of worn or broken parts.

Key term

Maintenance operations: practical actions carried out by maintenance staff and machine operators in order to keep equipment and machinery in good working condition.

Health and safety

When isolating machinery from the electricity supply, maintenance engineers will use a lock out/tag out system. This involves fitting padlocks to the isolator switches so that they cannot be turned back on by mistake while the maintenance engineers are working.

Test yourself

Explain the importance of safe shutdown procedures when carrying out maintenance tasks.

Roles and functions in maintenance operations

A range of roles are involved in maintenance operations:

- Machine operators are responsible for the day-to-day operation of machines and equipment. They conduct basic daily maintenance routines, such as lubrication, monitoring fluid levels and checking for damage or wear. Operators familiar with their machines and equipment will often be the first to notice signs of potential problems. They report any immediate concerns they have about the condition, operation or safety of the equipment to their supervisors or the maintenance manager.
- Maintenance engineers conduct the maintenance and repair tasks required by planned maintenance schedules or in response to breakdowns. This includes the safe shutdown of complex systems so that they are safe to work on.
- Maintenance managers are responsible for planning and organising maintenance activities, and for putting appropriate systems in place to ensure time lost to planned maintenance and unplanned, disruptive breakdowns is minimised. Many management decisions are driven by data collected during condition monitoring.

Maintenance tools and equipment

A wide range of general-purpose tools and equipment is required when conducting maintenance operations. These tools and equipment must cover both mechanical and electrical tasks, and include:

- portable power tools (for example drills, angle grinders, impact drivers and soldering irons)
- hand tools (for example spanners, screwdrivers, sockets, combination pliers, hacksaws, wire strippers, wire cutters and hammers)
- measuring instruments and gauges (for example tape measures, steel rules, digital callipers, feeler gauges, infrared thermometers, pressure gauges, flow meters and multimeters).

Industry tip

Keep your tools and equipment well organised so you can find the right tool for the job quickly and easily.

Always remember to turn off battery-powered measuring instruments like digital callipers or multimeters when you have finished with them, in order to conserve battery life.

Developments in maintenance

Environmental concerns are increasingly at the forefront of people's minds. Effective maintenance is essential in order to protect the environment by reducing energy usage, minimising emissions and preventing leaks of oil, hydraulic fluid or other chemicals. Even the impact of old equipment can be reduced by regular servicing and changing over to modern, low-toxicity, long-life, synthetic lubricants, coolants and other working fluids. These can reduce the amount of waste produced during routine maintenance and lessen the environmental impact following disposal.

Health and safety

In the UK, the storage, use and disposal of fluids such as lubricants and coolants is controlled by the Control of Substances Hazardous to Heath (COSHH) Regulations 2002.

As mentioned earlier, the development of internet-enabled sensor technology allows remote condition monitoring of complex systems. This supports real-time analysis of a wide range of key performance parameters, enabling greater efficiency and effectiveness of condition-based maintenance.

Manufacturers of complex machines can now use artificial intelligence to analyse vast amounts of performance monitoring data, allowing them to predict with ever greater accuracy when maintenance procedures are required. This approach further minimises costs while maintaining reliability, optimising maintenance activities and reducing downtime.

Case study

Rolls Royce monitors the performance and condition of its jet engines in real time around the world. Its latest aircraft engines are equipped with engine health monitoring systems (EHMS) – advanced systems of onboard sensors and communications equipment that monitor the condition of each engine and relay that information to a ground-based engineering centre. Engineers on the ground are even able to reconfigure the engine sensors remotely and run diagnostic tests with the engine still in service. All this is aimed at maximising aircraft availability by minimising time spent on the ground for maintenance and repair.

▲ Figure 1.5 Rolls Royce jet engine

Questions

1. Why is effective maintenance vital in the aerospace industry?
2. What new technologies does Rolls Royce rely on to carry out the condition-based monitoring of its jet engines?

1.3 Approaches to manufacturing, processing and control

Scale of manufacture

The number of products being made has a strong influence on the level of automation used in their manufacture. Making one-off products, where each piece is different, requires highly skilled workers, general purpose tools and very little automation. In contrast, mass production, where thousands of the same item are made, requires low-skilled workers, highly specialised tools and high levels of automation.

Test yourself

Explain the characteristics of mass production.

▼ Table 1.2 Comparison of different scales of manufacture

	One-off	Batch	Mass	Continuous
Batch size	1	2 to 1000	1000 to 100 000	100 000+
Set-up cost	Low	Medium	High	High
Specialist tools	None	Some	Most	All
Skill	High	High/Medium	Low	Low
Automation	None	Some	Most	All
Automation technology	Manual	Manual, CAD/CAM	Robotic	Fully automated
Cost per product	High	Medium	Low	Very low
Flexibility	High	High/Medium	Very low	None
Lead time	High	Medium	Low	Very low
Variation	High	High/Medium	Very low	None
Examples	Bespoke furniture Custom car exhaust	Bread rolls Classic car replacement chassis	Washing machines Mobile phones	Nails Wood screws Chemicals

Manufacturing infrastructure

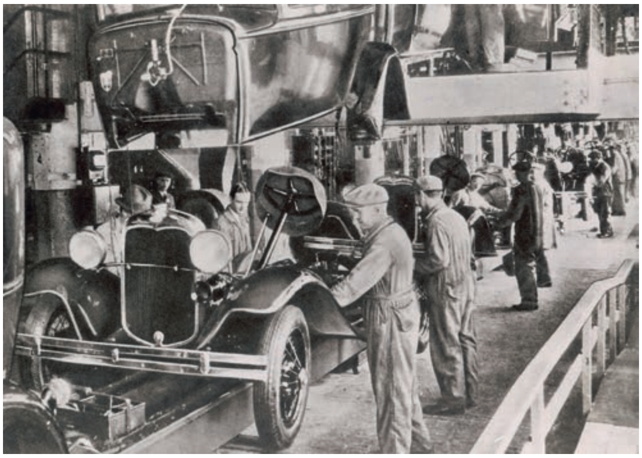
The layout of a factory will depend on the scale of manufacture and manufacturing methodologies being employed.

Product layout (or production line)

The factory layout that most people are familiar with is the production line used in mass production. This approach, pioneered by Henry Ford, breaks down the complex task of building a sophisticated product into a series of simple steps.

Materials, tools and equipment required for each step are arranged in a long line of workstations. The product itself moves slowly along this line and is assembled piece by piece as it progresses. At each workstation, a semi-skilled worker uses a small number of specialist tools and/or automated equipment to carry out the same task on each passing product.

Specialising in manufacturing a single product in this way results in a low manufacturing cost per item, due to low labour costs and high production rates. This means products can be produced quickly and cheaply. However, the facilities, specialist tools and high levels of automation required are expensive, time consuming to set up and lack the flexibility needed to cope with any variation in the product being manufactured.



▲ Figure 1.6 Production line at the Ford Motor Company, 1929

▲ Figure 1.7 A modern Ford production line

Functional layout

In a functional layout, similar equipment and skilled workers are arranged into workstations based on process type. For example, welders and welding equipment are in one place, and machinists and lathes are in another. In this model, workflow is routed between workstations until all the required operations are completed.

This is a flexible system, using general-purpose equipment with little automation, that works well in batch production where there is a high degree of variation in the products being manufactured. However, work-in-progress spends significant time being moved between workstations and waiting to be processed. The highly skilled workers required also drives up costs in comparison to a high-volume, low-skilled product layout.

Cellular layout

Cellular layouts use small, self-contained manufacturing cells for the batch production of variants within a family of similar components or products.

Sequential workstations are usually arranged in a horseshoe shape to enable workers to move around the cell quickly and easily to complete multiple tasks. This eliminates much of the movement of work-in-progress and waiting inherent in a functional layout.

This approach maintains flexibility by using highly trained workers who are familiar with all the product variants that they might be asked to manufacture and who also know how to complete any of the operations needed. This ensures that changeovers from making one variant to another are quick and easy.

So, partial specialisation enables some of the advantages of a product layout, while multi-skilling and rapid changeovers enable some of the advantages of a flexible functional layout. This means that customers can buy a wide range of product variants with short lead times, without the manufacturer having the expense of maintaining a stock of finished goods for each type.

Matrix arrangement

Matrix arrangements provide additional flexibility and capability to a cellular layout by allowing some products to be routed between individual processes or machines in different product cells. This is sometimes necessary in order to allow better utilisation of high-cost equipment or in cases where complex or potentially hazardous processes are used.

Levels of automation

Manual systems

Completely manual systems do not use automation. They provide a very high level of flexibility but also demand a high level of skill from workers and tend to be slow and expensive.

CAD/CAM systems

CAD/CAM systems integrate computer-aided design (CAD) and computer-aided manufacturing (CAM) and can be used to automate a manufacturing process.

Most engineered products are designed using CAD software to create three-dimensional models and associated engineering drawings of their components. This information is then used to generate the necessary programming code to instruct a computer numerical control (CNC) machine to manufacture a component.

CAD/CAM systems are often used in batch production in order to machine mechanical components on a CNC lathe or milling machine, and they have numerous advantages over manual systems:

- Accuracy is achieved consistently for every component, as it is not dependent on the skill of an individual machinist.
- Speed of manufacture is increased, as tool repositioning and changeover is automated.
- Capacity is increased, as CNC machines can operate 24 hours a day without breaks or holidays.

Robotic systems

Robotic systems are used where a repeated sequence of movements is required when manufacturing a large batch of products. Movements are carefully choreographed, and programming these systems can be complex and time consuming.

During the lifetime of a product, there are often small changes in design or manufacturing processes. Robotic systems are flexible and programs can be updated to accommodate change. This flexibility also means that robotic systems can be completely repurposed and reprogrammed to manufacture a different product when required.

A robotic arm can position an attached accessory anywhere within its **operational envelope** quickly and with pinpoint precision to complete a wide range of operations. Attachments include manipulators, spray-painting guns, welders and measuring equipment. Applications include relatively simple tasks such as picking up finished components and placing them in packing boxes, or much more complex tasks like spot welding pressed-steel components together into car bodies.

Key term

Operational envelope: area of three-dimensional space representing the maximum extent or reach of a robotic arm.

▲ Figure 1.8 Welding robots in the automotive industry

Health and safety

Robotic systems are able to operate in hazardous environments that would be far too dangerous for a human to work in.

Test yourself

Explain why robotic vehicles are widely used by bomb disposal teams.

Fully automated systems

Fully automated systems are used in continuous manufacturing, where a system or machine is built around the manufacture of a single product. The same product is manufactured for the entire service life of the system or machine. For example:

- Chemical products such as pharmaceuticals and petrochemicals are manufactured using dedicated automatic systems that are never switched off.
- High-volume consumable products such as nails, machine screws and springs are manufactured on dedicated automatic machines.

Control

Complex manufacturing systems demand a high degree of control to ensure they function efficiently and manufacture products and components of the right quality, in the required quantity and at the right time.

Performance monitoring

Essential to the control of manufacturing systems is the collection of key performance data, such as production rates or the number of product defects identified over time. This data forms the basis of performance management systems such as statistical process control (SPC).

SPC uses statistical tools to analyse data and reveal trends that cannot be explained by the random small variations present in any complex system. An unexplained rise in defects in the components made on a particular machine is an early warning sign and will prompt an investigation to identify, and then correct, the cause.

This proactive approach helps identify and address emerging problems before they can have a significant impact on manufacturing output or quality.

Quality control (QC)

At several points during the manufacture of a product, quality control (QC) checks are carried out to ensure compliance with the required specification. The earlier a defect in a product is identified, the easier and less expensive it is to put right.

Defective products reaching the customer must be avoided. Replacing or recalling faulty goods has significant immediate cost implications, but the long-term financial damage caused by gaining a reputation for poor quality can prove fatal to a business.

Test yourself

Explain why a faulty product that reaches a customer is much worse than one identified at the factory.

QC checks are carried out at the following points:

- Goods-inwards inspections are carried out on components and raw materials as they arrive in the factory. These checks are vital to ensure that goods coming in comply with their purchasing specifications, are fit for purpose and can be used in the manufacture of products.
- In-process inspections are carried out after each manufacturing operation. These ensure that any manufacturing error is identified as quickly as possible and that any defects are quarantined and not used in subsequent processes.
- Finished-goods inspections are the final checks made before a product goes to the customer. It is the last opportunity for any problems to be identified and corrected.

There are different types of QC check:

- Visual inspection involves carefully looking over a product or component. This simplest of checks can pick up a range of issues, from scratches and other forms of damage, to missing or poorly fitted components.
- Dimensional checks are measurements of the physical size of components to ensure they have been manufactured to within required tolerances.
- Functional checks are carried out to ensure that component assemblies function as intended. This could be a mechanical check (for example measuring the loading characteristics of a completed car shock absorber) or an electrical check (for example ensuring a PCB powers up and functions as expected).

Industry tip

Maintaining the quality of products and processes is a collective responsibility for all the employees in an organisation. Remain vigilant, and always report any problems or quality issues that you encounter in the workplace.

Test yourself

State at least five quality checks that will be carried out on a washing machine before it leaves the factory.

Quality assurance (QA)

Quality assurance (QA) involves much more than just carrying out QC checks. QA is an integrated approach to monitoring, maintaining and improving the quality of manufactured products.

Typical activities undertaken in an effective QA system include:

- performance monitoring
- QC checks
- standardisation of work methods to ensure all staff carry out manufacturing operations in the same way to avoid inconsistencies in the product
- planning what, when, where and how often QC inspection measurements are taken
- analysis of QC data using systems like SPC to identify areas of concern
- identification of the root cause(s) of quality issues and the redesign of products or processes to eliminate those issues.

Assessment practice

1. Powder coating is a common finishing process. Give two reasons why powder coating might be used on a steel bicycle frame.
2. Explain the differences between a linear and an iterative approach to design.
3. An external staircase used as a fire escape is manufactured by a company specialising in welding and fabrication. Explain one way in which design for manufacture and assembly may have influenced the design of the staircase.
4. A company manufactures mechanical assemblies for use on offshore wind turbines. Identify one way in which design for assembly techniques can be applied to reduce errors during production.
5. A company has decided to review the sustainability of its product range. Explain how considering each of the 6 Rs of sustainable design might help it to come up with new ideas.
6. Explain two ways in which the effective maintenance of machinery and equipment reduces negative impacts on the environment.
7. Explain the advantages of using automated processes when manufacturing large batches of the same product in mass production.
8. Explain why complex prototype components are often manufactured in a polymer material using an additive manufacturing process such as 3D printing.
9. Quality control (QC) inspections are carried out at several points during the manufacture of a product. Explain why goods-inwards inspection of purchased components and raw materials is important.
10. Explain the difference between quality control (QC) and quality assurance (QA).

Project practice

You work as a maintenance engineer for a manufacturing company. The company has just installed and commissioned five new centre lathes in its apprentice training centre. These machines will require regular maintenance to ensure they remain in good working order.

Write a short report to explain how these machines will be maintained. Your report should include:

- an explanation of the different types of maintenance
- a fully justified recommendation of the most appropriate type of maintenance to use for the lathes
- a description of how the system of maintenance will be organised
- a description of the roles and responsibilities of those involved.

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2 Engineering and manufacturing past, present and future

Introduction

In the 300 years since mechanisation brought about the first industrial revolution, engineering has underpinned every aspect of human endeavour. Today, industry and wider society are adopting and adapting to technological innovation at unprecedented speed.

In this chapter, you will learn about the activities undertaken in a wide range of engineering sectors. You will also reflect on some of the key developments that brought us to this point and how new and emerging technologies might shape the future.

Learning outcomes

By the end of this chapter, you will understand:

1. the main activities, products and/or services relating to different sectors of the engineering industry
2. how technological advances and their operations have evolved and contributed to engineering and social and economic development, in areas such as transportation, healthcare, housing, employment and sustainability
3. how innovation and emerging trends are evolving and could influence manufacturing, environmental considerations and social and economic development.

2.1 Sectors of the engineering industry

The engineering industry encompasses a diverse range of specialist sectors. The activities, goods and/or services relating to some of these sectors are outlined in Table 2.1.

▲ Figure 2.1 Aircraft maintenance is conducted by the aerospace sector

▼ Table 2.1 Sectors of the engineering industry

Engineering sector	Main activities, products and/or services
Aerospace	Research and development, design, manufacture and maintenance of manned and unmanned aircraft, rockets, missiles, satellites and spacecraft
Rail	Research and development, design, manufacture and maintenance of rolling stock and rail infrastructure
Agriculture	Research and development, design, manufacture and maintenance of specialist equipment and machinery used in forestry, horticulture and farming
Automotive	Research and development, design, manufacture and maintenance of cars, motorbikes, trucks and other road-going vehicles
Chemical	Research and development, design, manufacture and maintenance of industrial chemical processes, processing plants and equipment Applications across multiple sectors, including chemical manufacturing, petrochemicals, electronics, pharmaceuticals, food processing and healthcare
Structural	Research, development and design of load-bearing structures, such as buildings and bridges
Materials	Research, development and manufacture of metals, ceramics, polymers and composite materials used across engineering and a wide range of other sectors
Logistics	Research, development and design of systems to optimise the processes and activities involved in supply-chain management, such as purchasing, storage, warehousing and distribution
Defence	Research, development, design, manufacture and maintenance of a wide range of equipment and technologies involved in maintaining national security and equipping the armed forces Includes everything from communications, munitions and body armour, to tanks, submarines and combat aircraft
Electrical and electronic control	Design, manufacture and maintenance of control systems, instrumentation, monitoring and automation for electro-mechanical engineering systems used in a range of sectors
Medical	Research and development, design and manufacture of instruments, equipment, machines and devices for use in healthcare, including heart monitors, MRI machines, surgical instruments and prosthetics
Manufacturing	Research and development, design, manufacture and maintenance of processes, systems, equipment and machinery involved in manufacturing a wide range of products in a range of sectors
Marine	Research, development, design, manufacture and maintenance of oil rigs, offshore wind installations, ships, submarines and other sea-going vessels
Petrochemical	Design, manufacture and maintenance of machinery and equipment used for oil exploration, extraction, transport, processing and refining

Engineering sector	Main activities, products and/or services
Power generation (renewables)	Research, development, design, manufacture and maintenance of infrastructure, machinery and equipment used in generating electricity from renewable resources, including photovoltaic solar, wind turbine, hydroelectric, tidal and geothermal systems
Power generation (non-renewables)	Research, development, design, manufacture and maintenance of infrastructure, machinery and equipment used in generating electricity from non-renewable fossil fuels, such as coal, gas and oil
Power generation (nuclear)	Research, development, design, manufacture and maintenance of infrastructure, machinery, equipment and waste-management technologies used in generating electricity from nuclear fuel
Telecommunications	Research, development, design, manufacture and maintenance of telecommunications infrastructure and equipment, including fixed and mobile telephone networks, fibre-optic broadband networks, satellite communications, television and radio
Water and waste management	Research, development, design, manufacture and maintenance of water and wastewater treatment infrastructure, machines and equipment, including the water distribution network and the collection, treatment and reuse of wastewater

Industry tip

Many engineering sectors overlap or are interlinked. Whatever sector you work in, you will deal with a wide range of products, services and colleagues from across the engineering industry.

Test yourself

A company designs control systems and instrumentation to be installed in offshore wind turbines. What engineering sector does it belong to?

Research

Choose an engineering sector you are interested in and conduct your own detailed research into the products and services it provides. Find out about potential employment opportunities in that sector and the qualifications you would need in order to gain employment.

2.2 Significant technological advances in engineering from a historical perspective

Development of materials

Throughout history, human progress has been shaped by taking advantage of the materials available to us. Early humans spent hundreds of thousands of years reliant on just the natural materials they found in their local environment. In contrast, we are now in a period where our understanding of material science, processing and manufacturing means that we can call upon thousands of materials with a massive range of properties.

Some materials have had a significant impact on the development of modern society:

- In 1855, the development of the **Bessemer process** allowed the cost-effective mass production of steel. Steel is the most widely used metal in engineering and has perhaps had the biggest impact on industrial development. It has allowed us to build railways, bridges, dams and other structures that form essential infrastructure and dominate the built environment. Steel is essential in the manufacture of machine tools, cars, ships and any product or structure held together with screws, nails or nuts and bolts.
- In 1907, Bakelite became the world's first synthetic polymer. However, it was not until the 1960s that the use of polymers became preferred over traditional materials and they became ubiquitous. Today, polymers can be found in a massive array of applications across all engineering sectors.

Key term

Bessemer process: method of producing steel by burning off carbon and other impurities in pig iron by blasting air through the molten metal.

- Ceramics are among the oldest types of materials used by humans. They include glass and ceramic pottery, both of which have had important applications in cookware and food storage for centuries. Modern ceramic materials, such as tungsten carbide, have important applications in manufacturing, where they are used in cutting tools and abrasives.

Electrical power

The harnessing of electrical power underpins much of the scientific progress and societal and technological changes that have occurred in the last hundred years.

Today, we tend to take the supply of electricity for granted, and it is easy to forget that the widespread use of electrical power is very recent. The world's first large-scale, coal-fired power station was opened in London in 1882, but extensive availability of electrical power did not happen until well into the twentieth century. It was not until 1935 that the world's first integrated national grid was completed, connecting power stations and electricity customers, and enabling widespread distribution of electricity in the UK. By 1940, two thirds of homes in the UK, mostly concentrated in urban areas, had a supply of electricity.

One of the first practical applications for electricity was to provide a safe and clean form of artificial light (this is explored further in the next section). Soon after, a wide range of domestic labour-saving appliances were invented, designed to automate or assist in an array of everyday household chores. These included washing machines, electric irons and vacuum cleaners.

Other domestic appliances, such as refrigerators and freezers, allowed food to be preserved for longer. This led to changes in shopping habits, as it was no longer necessary to shop every day for fresh ingredients. Food from larger weekly shops could be refrigerated until needed.

Refrigerated transport led to more fresh fruit, vegetables and fish being available in large cities, which in turn led to improvements in diet and general health.

Electricity also made consumer electronics possible, for example radios, televisions and, more recently, computers and the internet.

The impact of these technologies is explored later, but their importance is such that all technologically advanced societies have become entirely dependent on a reliable and accessible supply of electrical power. Modern life as we know it could not exist without it.

▲ Figure 2.2 The National Grid distributes electricity throughout the UK

Electrical sources of artificial lighting

Prior to the availability of reliable electric lights in 1878, street lighting in major cities and large towns ran on gas. Gas lighting was also used in commercial buildings and some large homes, but most of the population still relied on candles and oil lamps for lighting, and on open coal fires for warmth.

Domestic electric lighting began to replace gas as more homes were connected to the electricity grid. This revolutionised home life, which was no longer constrained by seasonal daylight hours.

In factories, electric lighting allowed manufacturing to continue throughout the night, enabled the introduction of shift work, and increased both capacity and industrial output.

The internal combustion engine

From its invention in the 1860s, the **internal combustion engine** began to replace the steam engines used to drive machinery and run electrical generators in factories and light industry. By the 1890s, the technology had matured sufficiently to allow Carl Benz to launch the first commercially successful motor car powered by an internal combustion engine. However, it was not until Henry Ford introduced the affordable, dependable and easy-to-drive Model T in 1908 that motoring became widely accessible to ordinary families.

Key term

Internal combustion engine: engine where fuel is burned inside the engine itself.

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