Course Project: Manufacturing Process of a Clock
Stage 2 Submission

Team members: Sidharth Mundhra (190110091)
Gopalan Iyengar (19D170009)
Om Prabhu (19D170018)

Description of Project:

The clock is one of the most successful inventions of all time. It can be seen in analogue form in every household, and a digital form of it is an integral part of every computer-based device, such as laptops, PCs, mobiles. We can also see them in portable forms in the form of wristwatches, and recently smartwatches have become trending, which also builds on the same concept.

A clock is a device that tells time. It is represented as a circular space graduated into 12 different numbers (1-12) making 12 sectors when in analogue form, and a set of numbers in digital form. Everyone knows how to read the time. It needs no introduction. We will be covering analogue clocks as part of this project, and digital clocks tentatively as the project schedule permits.

Applications of a Clock:

As it is evident, clocks are a core part of our life and available everywhere, so their importance cannot be stressed enough. The main feature of a clock is to tell the current time. This is a very helpful way to organize daily life. Nowadays, everyone is involved in a plethora of activities, and it is important to have a way of tracking the duration of them, making sure they don't clash and managing them well. A clock provides access to time, a universally accepted standard to distinguish between events. Using the common notion of time, people can keep a track of events, and designate certain amounts of time to each event. This allows everyone to have a common understanding of the starting and ending of events, a measure of their duration, and a measure of the interval between them.

A clock would mainly be used to know the current daily time, the date, while available as an option in many clocks, is not a traditionally fundamental part of a clock, it is gauged using calendars. So, it aids in daily planning, which is more short-term. For long-term planning, a measure of days, months, and years is required.

A few clocks can even be seen as monuments, Big Ben is the most prominent example. It has become a key part of the representation of London city and is one of the first things that come to mind when someone thinks of London.

Manufacturing Cost of a Clock (approx.):

The manufacturing cost of a clock includes a variety of components, both fixed and variable. Examples of fixed costs involved in the manufacturing process are rent for factory space (or a one-time payment if the land is bought) and electricity/fuel costs (since machines in the factory use the same amount of energy regardless of whether they are actively producing or not).

Examples of variable costs involved in the process are wages paid to workers (since it is likely that new workers may be hired and some old workers leave), amount of capital invested in potential business/machinery expansions, costs of raw materials (which depends on the current market demand for clocks), etc.

Other factors influencing the cost of a clock are the size of the firm (a bigger firm is more likely to experience economies of scale, thereby reducing the average cost of production), type of clock (since a digital clock requires different raw materials compared to an analog clock or a wristwatch/smartwatch), location of the company (which directly influences costs of local/imported raw materials), etc.

Taking all of these points into account, manufacturing of a simple alarm clock that one may use on a day-to-day basis is found to be approximately between $8 - $12 per clock depending on the output level produced by the firm.

Work Distribution (last updated at the time of Stage 4 submission – 26/09/2021)**:**

Stage 2:

Product Description: Gopalan

Product Applications: Sidharth

Approximate Cost: Om

Stage 3:

Design: Gopalan

Components: Om

Engineering Drawing: Sidharth

Stage 4:

Materials: Om

Process Selection: Om (up to digital display), Sidharth (mainspring onwards)

Stage 5 (tentative):

Machines, Equipment and Manufacturing: Sidharth

Finishing, Coatings: Gopalan

Assembly: Om

Inspection: All 3

Final Stage:

Everyone will work together to make the final report and presentation video

---

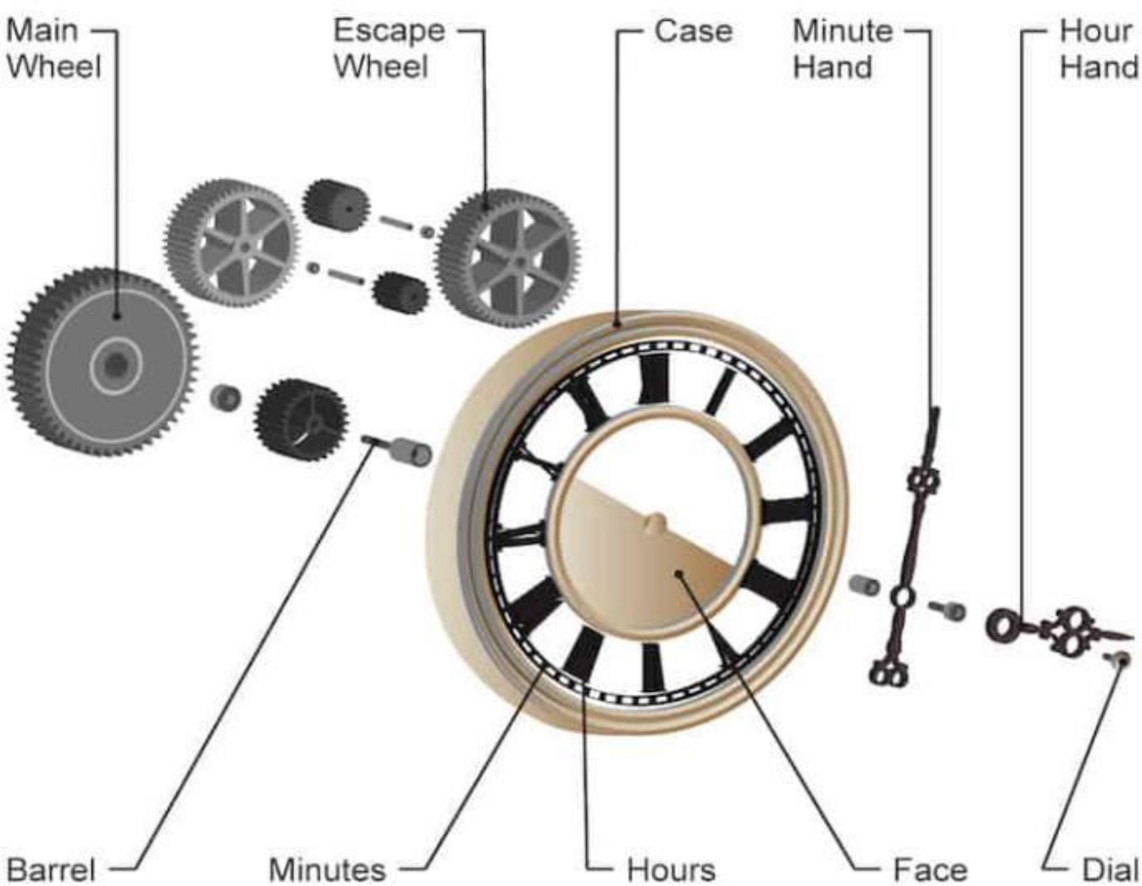
ME 338 Course Project: Stage 3 Submission

Topic: Manufacturing Process of a Clock

Team Members: Om Prabhu (19D170018)
Sidharth Mundhra (190110091)
Gopalan Iyengar (19D170009)

Design:

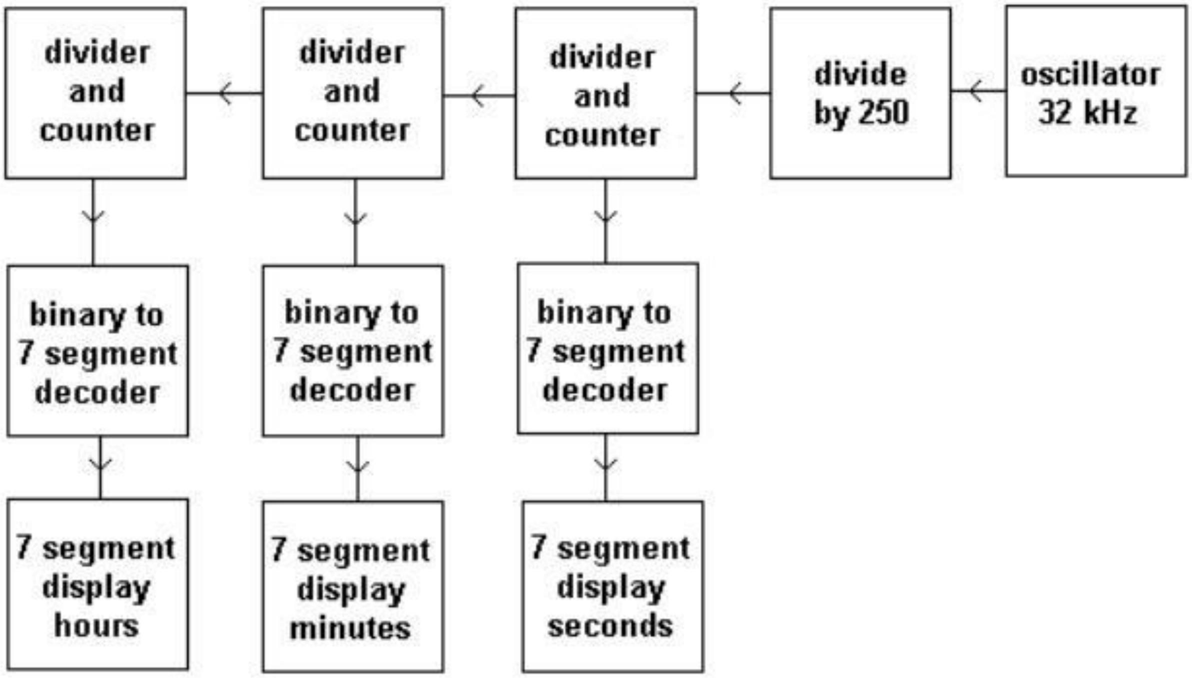
An analog clock consists of 3 concentric hands: an hour hand, a minute hand and a second hand, which point towards their namesake on a clock-face graduated into 12 different sectors. The face is set in a frame, which contains the gear & spring system associated with the hands, and the power source, which is generally a set of AA or AAA cells.



Exploded View of an Analog Clock

A digital clock consists of a 7-segment LED/LCD display (or a screen), the power source, and the circuitry along with the crystal using which the circuit determines time.

A Digital Clock



Internal Circuitry of a Digital Clock

Components:

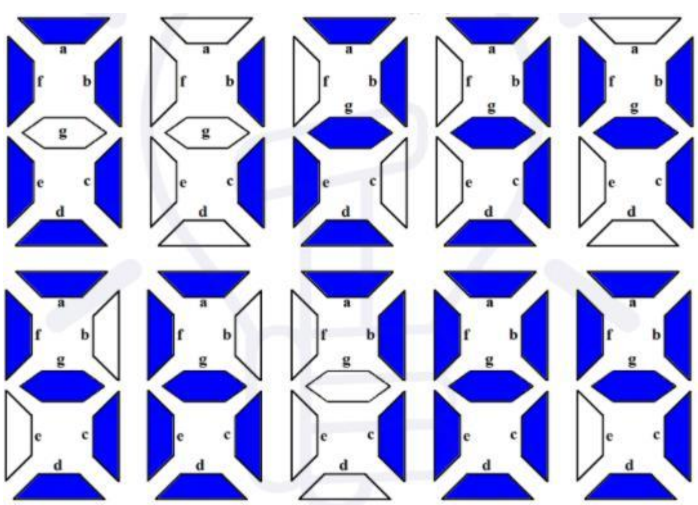
A clock comprises several components, and the nature of these components depends on the type of clock. The parts that immediately come to mind are the visible parts - for an analogue clock, these are the face and arms while for a digital clock, it is the LED display panel. However, it is the components behind the scenes that make the clock actually function. These include the gears/wheels, mainspring, quartz crystal and optionally, a pendulum. All of these components are discussed below in greater detail:

- **Face:** This serves as the main background of a clock. It is generally shaped as a circle and it contains some basic indicators (such as an hour/minute display) to make it easy to read the time by observing the arms of the clock. Some materials commonly used to manufacture this part include cardboard, acrylic, hardened plastic, painted metal, etc.

- **Arms:** There are usually 3 arms/hands in a clock - the hour hand, minute hand and the second hand. These are pivoted at the centre of the face and are connected to the wheels in the interior of the clock. The rotation of the hands directly corresponds to the rotation of the wheels.

  Within one hour, the hour hand rotates by 30°, the minute hand rotates through a full 360°, and the second hand rotates by 21600° (i.e. 360° every minute). For ease of identification, the hour hand is usually the thickest and shortest in length. The minute and second hand are usually of a similar length, with the minute hand being thicker than the second hand. They are usually made either of a light metal like aluminium or plastic.

- **Digital Display:** This is the main indicator of time in a digital clock. Each digit is displayed as a combination of 7 LED segments as shown in the figure below. Each segment consists of an LED. One pin of the LEDs is connected to form a common connection to the circuit, while the second pin is connected individually so the segment glows only when its LED is forward biased.



- **Gears/Wheels:** A clock typically consists of three wheels - the centre wheel, the third wheel and the escape wheel. The centre wheel rotates once per hour, the third wheel rotates once per minute and the escape wheel is used to control how fast the mainspring unwinds.

- **Mainspring:** This is a spiral torsional spring made of metal ribbon, usually spring steel. It is used to keep track of time by measuring the release of potential energy in the wound-up spring.

  The inner end of the spring is hooked to an axle called the arbor while the outer end is attached to a stationary post. The spring is wound anti-clockwise by turning the arbor, which causes build-up of spring potential energy. After the energy reaches a certain value, the spring and the arbor snap back to their original position which results in the second hand of the clock moving with a “jerk” in the other (i.e. clockwise) direction.

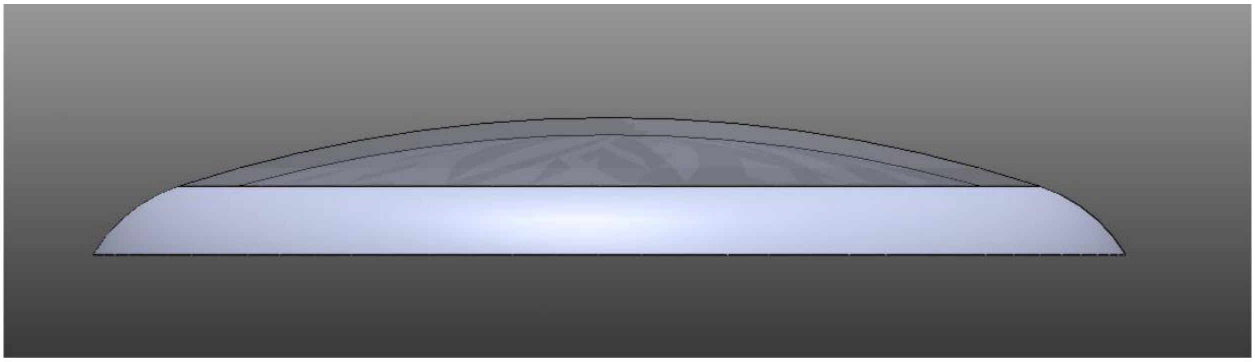
  In more modern clocks, the spring and the arbor are enclosed in a box called the barrel. The pull of the mainspring turns the barrel, which is linked to the wheels through a set of gear teeth.

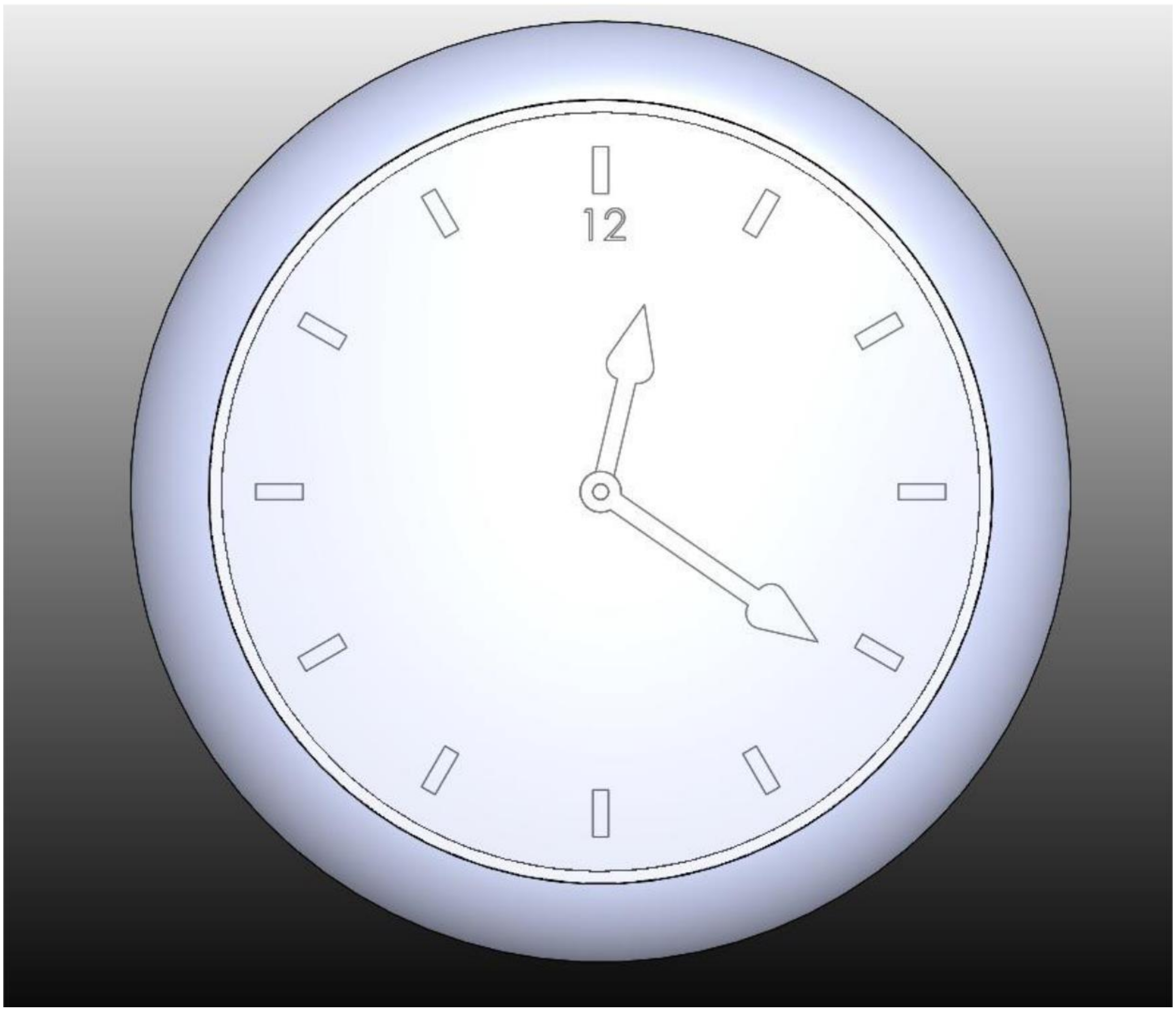
- **Quartz Crystal:** This is used mainly in digital clocks and wrist watches that do not use the gear mechanism. The quartz crystal resonates at an exact natural frequency of 32.768 kHz. The crystal is connected to an AC circuit which in turn resonates at the same frequency. The rate of oscillation of the AC circuit determines the rate of passage of time.

  Quartz occurs naturally as a mineral (or can also be artificially manufactured), but it cannot be directly used in this form. For the crystal to resonate at exactly 32.768 kHz, it must be machined very precisely. Any errors can lead to a different value of resonant frequency, which would make the crystal unsuitable for use in a clock.

- **Pendulum:** Some antique clocks use a pendulum system to keep time. It comprises a weight that hangs from a pulley mechanism and swings at an exact rate of one second. The pulley is internally connected to the wheels so the arms of the clock may move. Galvanised steel is commonly used in pendulums since it is cheap and has a low coefficient of thermal expansion.

Engineering Drawings:




12

References:

1. Design:
    a. https://www.homestratosphere.com/parts-of-a-wall-clock/
    b. https://www.hobbyprojects.com/block_diagrams/digital_clock.html
2. Components:
    a. Names of Parts of a Clock (ourpastimes.com)
    b. Seven Segment Display: 7-Segment Display Types and Working (electricaltechnology.org)
    c. Mainspring - Wikipedia

ME 338 Course Project: Stage 4 Submission

Topic: Manufacturing Process of a Clock

Team Members: Om Prabhu (19D170018)
Sidharth Mundhra (190110091)
Gopalan Iyengar (19D170009)

Materials:

The materials used in a clock are heavily dependent on the type of clock in consideration. For example, a digital watch lacks certain components like gears, hands, etc while a mechanical watch lacks a digital display and perhaps a touchscreen. This essentially means that different materials must be used in both of them to account for their usage.

The main factors influencing the selection of a material in any manufacturing process, amongst many others, are suitable properties required for the application, availability, cost (assembly equipment/labour, material, tooling, energy cost) and environmental concerns. There may be many materials suitable for the application out of which only a few have to be chosen after taking all these points into consideration.

The table on the next page discusses the most common materials used in various parts of a clock in much greater detail, along with several reasons as to what makes the materials suitable for their respective application.

Part	Material(s) Used	Properties
Case/Housing	Stainless Steel (most commonly used is SAE 316L)	- significant carbon content which increases toughness & strength - significant chromium content which increases resistance to scratches & wear by corrosion - visually appealing surface finish - heavy for use in wrist watches (density: 7.9 g/cm^3) - high hardness leads to difficulties in shaping operations
	Aluminum alloys (50-60% aluminum oxide)	- economical and easily available - very high formability for machining operations - relatively high hardness & strength for its low density
	Wood (commonly used in antique wall clocks)	- readily available and extremely economical - various types of wood to choose from based on consumer preference - highly brittle and very low formability, needs to be machined using classic sawing, grinding and planing
	Other Composites (suitable for use in pocket watches/alarm clocks)	- carbon composites: low density, high strength; low scratch resistance - ceramics: high scratch resistance; risk of breakage due to low pliancy - plastics: highly machinable, low density, economical, reasonably tough; environmental concerns
Face	Toughened plastics	- low-cost machining & easier to print/etch time display (i.e. hour display) - relatively more brittle compared to ceramics
	Ceramics	- resistant to cracks and medium-heavy mechanical damage leading to better protection for internal components
Arms	Aluminum (and other light metals)	- low density allows for smaller torque requirements for the internal gear mechanism, leading to overall energy efficiency - high ductility allows for manufacture of thin arms
	Plastic	- lighter and more economical compared to metals

Digital Display	LEDs	- semiconductor wafers & epitaxial layers: combination of gallium, arsenic, phosphor compounds (different excitation frequencies corresponding to different colours) - leadframes/pins: metal electroplated with alkaline low-cyanide silver - thin gold filament to provide connection between the two pins - small plastic mold to seal the assembly
	Integrated Circuit	- provides independent control of LEDs in 7-segment display using pins that define bias of each LED - silicon dioxide: insulator and dielectric material (high availability, high stability due to diamond-like structure and high forward voltage, moderate energy band gap) - arsenic/boron, gallium/phosphor: N and P-type dopants (due to having 5 and 3 valence electrons respectively)
Gears/Wheels	Steel/Cast Iron	- high strength-to-weight ratio - ability to enhance physical properties through heat treatment & other chemical methods - competitive pricing
	Toughened Plastics	- economical and easy to source & manufacture - suitable for smaller clocks (eg: alarm clocks) - lower life span compared to metallic gears
	Brass/Bronze	- relative softness of alloys leads to easier machining as well as lower friction coefficients - longer lifespan compared to plastic gears
	Powdered Metals (iron-nickel steel)	- low friction coefficients leading to lower energy losses from gear teeth - suitable for smaller gears in mechanical clocks (linked to knobs for changing time manually) - requires precision tooling & high pressures for smaller gears

Mainspring	Invar (Fe-Ni36%)	- high dimensional stability due to very low thermal coefficient of expansion, leading to better time accuracy in varying temperature conditions - high ductility for use in precision instruments/parts
	Spring steel (SAE 1070, 1095)	- hardened and tempered steel with high elasticity - more suitable for use in larger clocks due to relatively lower ductility compared to iron-nickel alloys
Quartz Crystal	Quartz	- distinctive quality of oscillating at a very precise frequency when stimulated by alternating current (natural frequency differs based on size and shape) - requires extremely precise machining to reach the desired frequency (32,768 kHz for clocks) - second most naturally occurring mineral
Pendulum	Galvanized Steel/Brass	- ease of production and machining - resistance to wear by corrosion - low coefficient of thermal expansion leading to better time accuracy

While the above table includes the most common materials used in mechanical as well as digital clocks, there are a few other types of clocks which use slightly different working mechanisms and hence, different materials. Similar to how pendulum clocks use a gear mechanism and crystal-based clocks use quartz crystals for timekeeping, atomic watches use atomic interactions between Cesium-133 atoms while magnetic watches use a ball-bearing mechanism.

In an atomic clock, each of the Cesium-133 atoms have one of two possible energy states depending on the surrounding magnetic field (referred to as hyperfine levels). A very high frequency alternating current is used to oscillate the magnetic field which in turn influences the energy state of the atoms. When the magnetic field is flipped, all the atoms move from one energy state to the other. This allows for very precise time measurement - in fact, atomic clocks are so accurate that the SI system defines one second as the amount of time it takes for a Cs-133 atom to oscillate exactly 9,192,631,770 times.

Magnetic wrist watches use a modified version of the gear mechanism. The ticking motion of the gears is used to internally move small neodymium magnets, each of which move a ball bearing around the circumference of the watch in a circular track. Given the limited space on a wrist watch, there are usually only two ball bearings corresponding to the hour and minute indicators. This type of design makes it very easy to tell the time by simply touching the face of the watch and sensing the position of the ball bearings, which is suitable for people with vision impairments.

Process Selection:

As we have seen, manufacturing a clock involves a variety of different components. Since the nature of these components is very different, it follows that they cannot all be manufactured using the same set of manufacturing processes. In general, the larger parts corresponding to the exterior of the clock are manufactured by bulk cutting processes while the interior parts require more precise machining.

1. **Case/Housing:**

   Since this is the largest part of the clock, it is relatively easier to manufacture using bulk machining processes such as shaping or milling. To avoid a lot of wastage, the initial workpieces must be of approximately the same size as the manufacturing specifications with some allowance for machining. This can be done by solidifying molten metal in moulds of a specific size and shape and by chainsawing machines in case of wood.

   The machining processes are generally carried out using curved ballnose-shaped tools to give the case a fine surface finish. Very often, products require further finishing to get rid of any anomalies introduced by machining (eg: narrow circular tracks produced in the direction of the directrix). The most commonly used processes for this are electroplating and/or painting due to their affordability and bulk processing ability.

   Wooden cases are most often manufactured manually by carpenters since high-speed machining processes are likely to fracture wooden workpieces due to large shear stresses. They can then be easily polished manually using lacquer or varnish depending on the type of finish desired. This is also why many wood-based clocks are more expensive compared to their metallic counterparts.

2. **Face:**

   The face of a clock is perhaps the simplest piece to manufacture since it most often is just a thin square slab or circular disc made of plastic/ceramic. This can be achieved very easily by shaping or milling processes using a tool with large surface area for bulk machining. However, care must be taken to keep machining speeds relatively low since both plastics as well as ceramics are relatively brittle.

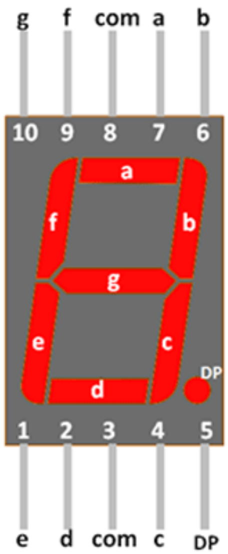
   It gets more complicated when the face has to be of specific colour(s). This often requires high temperature processes where plastics/ceramics become relatively more porous and allow dyes to pass into the material. A simple alternative to this would be simply spray-painting the faces (ideal for smaller clocks where it is more economical per unit manufactured), but high temperature dyeing generally offers better visual results as well as better wear resistance.

3. **Arms:**

   The arms of a clock are relatively smaller components compared to the case and face. Since they are relatively thin, care must be taken that they are not bent in any way while manufacturing. A very common process used to manufacture such thin components is pressing, which essentially involves the action of high pressure to reduce the material thickness. To attach the arms about the central pivoting shaft, the process of punching is used.

4. **Digital Display:**

The production of a digital display mainly involves constructing the LED circuit on top of the integrated circuit (which is manufactured by squeezing semiconductor wafers under high pressure). The pinout diagram below is a schematic representation of the circuit which defines the bias of the LEDs. Each of the 7 LEDs is linked to one of the terminals labelled a – g, while the remaining three ports are used for connections to the AC circuit.



Sometimes, in a bid to reduce manufacturing costs, manufacturers may use tinted glass or ceramic panels to cover the display instead of using coloured LEDs.

5. **Mainspring:**

There is a five-step process for the manufacturing of springs. First, the spring needs to be coiled, which can be achieved by using either cold winding or hot winding. Cold winding involves simply winding a wire that is at room temperature around a shaft. If we heat the wire, it will be easier to deform it (lesser force required as flexibility increases), so hot winding is preferred for springs. Commonly in the industry, before bending, the metal is heated to increase wire flexibility and coiled when hot. Next, it is quenched in oil to cool it down and to keep the shape in place.

For the second step, the built-up stresses are in the wire, the spring is heated at a set temperature and then cooled slowly. The spring is then strengthened to decrease metal fatigue. Next, setting is done by completely compressing the spring multiple times to keep it stable and keep the length constant. In the final step, to prevent corrosion, the spring is coated with chromium/zinc.

6. **Gear/Wheels:**

Hobbing and milling process can be used for manufacturing gears. In this process, the workpiece is fed at a constant rate while the cutting tool (hob) rotates. It is also a type of milling process. The hob does a series of cuts to produce external gear teeth. Similar to the manufacturing process of mainspring (second step), the material is heated to relieve the built-up stresses and then cooled. Grinding may be used to provide a smoother finish.

7. **Quartz Crystal:**

The quartz crystals need to be artificially grown under controlled conditions as naturally occurring quartz is not suitable according to the quality needs of the resonator. After growing the crystal, the faces are accurately ground to accurately define the X, Y, and Z axes.

High precision cutters are then use to cut the quartz crystal into small flat plates. These slices through the crystal need to be made slightly thicker than that required for the finished crystal.

Now these can then be further cut into smaller blanks which are then lapped to bring them closer to the required thickness. As the lapping process is abrasive, it damages the crystal lattice on the surface of the crystal. This not only lets in gas molecules and other impurities later that will cause ageing, but it also directly causes changes with time.

Once the lapping forms have been embraced the surfaces of the precious stone are chemically carved. This gives a really much better wrap up to the crystal and gives less opportunity for chemical entrance afterward. In any case the surface of the crystal has to be exceptionally carefully washed after the chemical carving to expel all follows of outside chemicals.

References:

1. Materials:

a. Factors affecting selection of manufacturing process (learnmech.com)
b. The different materials used in watchmaking (code41watches.com)
c. https://prezi.com/8az6fo_ln42n/how-its-made-wall-clock/
d. How watch is made - material, manufacture, making, used, parts, components, structure, product (madehow.com)
e. How light-emitting diode (led) is made - material, manufacture, making, used, processing, parts, components, composition (madehow.com)
f. How integrated circuit is made - material, making, used, processing, components, dimensions, composition, industry (madehow.com)
g. Doping in Semiconductors (tutorialspoint.com)
h. Powdered Metal Gears Manufacturer - Small Sintered Metal Gears | Atlas Pressed Metals
i. Quartz - Wikipedia

2. Processes:

a. How cuckoo clock is made - material, manufacture, making, history, used, parts, steps, industry, History (madehow.com)
b. How watch is made - material, manufacture, making, used, parts, components, structure, product (madehow.com)
c. https://www.brighthubengineering.com/manufacturing-technology/7118-gear-manufacturing-methods/
d. https://www.wired.co.uk/article/how-springs-are-made
e. https://www.brighthubengineering.com/machine-design/54329-compression-spring-design-part-one-basic-formula-and-considerations/
f. https://www.electronics-notes.com/articles/electronic_components/quartz-crystal-xtal/crystal-resonator-manufacture.php