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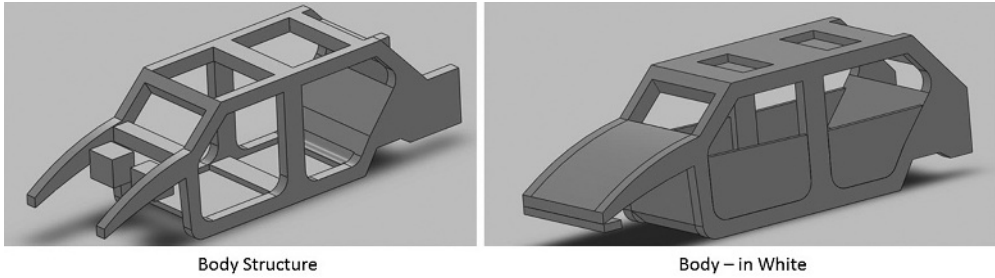
## Introduction

### 1.1 Anatomy of a Vehicle, Vehicle Functionality and Components

Customers today perceive the value of an automobile based on its structure, its mobility function, its appearance, and other miscellaneous options such as infotainment. This fact motivates the automotive engineers to develop engineering metrics to judge each of these perspectives in a quantitative manner to help them improve their design, benchmark their vehicles against their competitors and, more importantly, meet the legal regulations. For example, the performance of a vehicle structure is dependent on the following criteria: Crash-worthiness (or passive safety), service life (or durability), its noise, vibration and harshness (NVH) characteristics, in addition to new metrics that have recently been viewed as value-adding, such as structure recyclability and weight efficiency.

Crash-worthiness defines the vehicle structure ability or capacity to absorb dynamic energy without harming its occupants in an accident, while the durability is the probability that the structure will function without failure over a specified period of time or frequency of usage. The NVH describes the structure performance in absorbing the different vibration levels and providing a desired (designed) level of comfort. The noise is defined as vibration levels with low frequency (<25 Hz), while harshness is the term for vibrations at (~25–100 Hz). All the above structural requirements are controlled by intrinsic (density, Young's modulus) and extrinsic (thickness, geometry, and shapes) material properties and joining strategies. So the material, its shape selections, and the manufacturing process control the overall performance of vehicular structures.

The vehicle mobility function is controlled by its ride and handling dynamics in addition to the drive-line and power-train systems' reliability. Again, the choice of material (weight and stiffness) and the design geometries (center of gravity location) affect the vehicle's performance. The vehicle appearance can be described in its styling, which is controlled by the panels' shape, its geometrical fit (gaps, flush



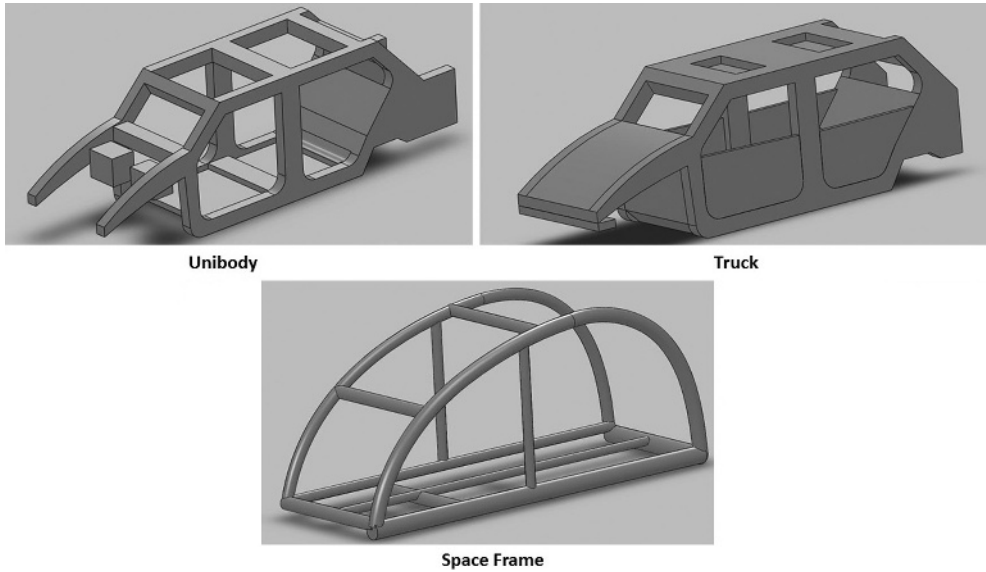
**Figure 1.1** Left: the vehicle body structure without closures, right: the complete vehicle BiW

setting, etc.), and its final paint finish. Human visual perception evaluates the vehicle's finish in terms of specific visual qualities: Color properties, encompassing three color attributes, in addition to color matching between the different vehicle parts such as the steel body and the plastic trim. Also, surfaces' spatial properties as well as the vehicle's geometric attributes such as gloss, texture, and haze control the customer's perception. For example, if the paint on a vehicle suffers from orange peel, i.e. the paint looks like the peel of an orange, the customer might mistakenly observe this as a defect (variation) in the sheet metal roughness.

The vehicle's main components and sub-systems can be categorically listed as: Power-train, chassis, exterior and interior trims, and the body in white (BiW) or vehicle body-shell. The power-train is composed of the prime-mover (the internal combustion engine, or electric motor), the gear system, and the propulsion and drive shafts, while the chassis includes the suspension and steering components, in addition to the wheel, tires, and axles. The interior and exterior trims compose the front and rear ends, the door system, and the cockpit trim. Finally, the body in white is made up of the closures (doors, hood, tail-gate) and the frame, see Figure 1.1). The frame can be of a uni-body design (Figure 1.2 (a) uni-body), a body-on-frame (Figure 1.2 (b)), or a space-frame (Figure 1.2 (c)). The uni-body design features stamped panels, while the space-frame is made up of extrusions and cast parts. The BiW closures are selected based on the vehicle's constituent material dent-resistance properties (i.e. yield strength) while the frame is designed to provide specific torsional and bending stiffness.

## 1.2 Vehicle Manufacturing: An Overview

After reading Section 1.1, we can conclude that vehicle performance is judged based on design strength, stiffness, energy absorption, dent resistance, and surface roughness. However, before designers select a material or design a specific shape, they should consider manufacturability. The manufacturability from an automotive body structure's point of view is described in terms of the design formability, the joining



**Figure 1.2** Top left: (a) a uni-body design, top, right: (b) truck platform; and bottom right: (c) space-frame design

ability (weldability and hemming ability), the achieved surface finish and surface energy, and its overall cost. This fact motivates a deeper understanding of the automotive manufacturing processes and systems, because it will ultimately decide the design's overall cost, final shape, and functionality, that is, the design validity.

The automotive manufacturing activities can be analyzed on two levels: the manufacturing *system* and *process* levels. The manufacturing system view is typically investigated from three different perspectives: the production line (the *structural aspect*) which covers the machinery, the material handling equipment, the labor resources, and its allocations to the different activities. The *transformational aspect* includes the functional part of the manufacturing system that is the conversion of the raw materials into finished or semi-finished products. The transformational activities include all the stamping, casting, welding, machining and painting efforts within the plant. The third aspect is the *procedural aspect* which describes the operating procedures and strategies, which is further viewed from two different levels; the strategic level which identifies the product type, and volume (product planning), given the operating environment conditions (customer demands and regulatory issues). Additionally, the strategic plan includes the resources' allocation in the manufacturing enterprise. The second level is the operational level which is focused on production control, i.e. meeting the strategic plan objectives through planning, implementing, and control and monitoring activities. These operational activities are further categorized by [1]:

1. *aggregate production planning* which suggests product plans based on the required product volume, using a generic unit such as the vehicle platform not type, to increase the level of confidence from the forecast information;
2. *production process planning* which controls the production techniques to be used, in addition to process routes and sequence;
3. *production scheduling* to determine an implementation plan for the time schedule for every job in the process route;
4. *production implementation* which is the execution of the actual production plan according to the time schedule and allocated resources;
5. *production control* to measure and reduce any deviations from the actual plan and time schedules.

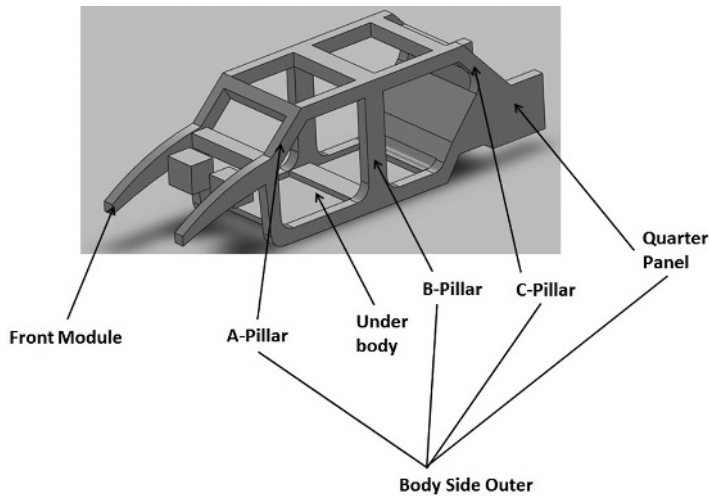
Another important view on the automotive manufacturing systems relates to the information, materials, and value-added (cost) *flows* within the plant. The raw materials and supplier parts flow from upstream to downstream through the material supply system, the material handling system and finally through the material distribution system. However, the information flows in the opposite direction, that is from downstream to upstream, to synchronize the rhythm of production and control its quality; this information flow is typically called the pull production system to indicate that the customer side controls the quantity and quality (product type) of the production. On the other hand, the old push system meant that the manufacturing plant outputs vehicles according to a mass production scheme without any feedback from the customer side.

The automobile manufacturing processes are divided into two plants: the assembly plants and the power-train plants. Both of these plants specialize in different transformational processes and convert different raw materials into final parts. However, both are synchronized in time to integrate their final outputs into complete vehicles.

### 1.2.1 Basics of the Assembly Processes

An automotive assembly plant is responsible for the fabrication of the complete vehicle BiW, starting from a steel and/or aluminum coil and ending with a complete painted car shell. Additionally, the power-train, chassis components, interior and exterior trims are all integrated into the BiW at the end of the assembly process in the final assembly area.

The assembly sequence starts with the receiving area for the coil (which is typically made out of steel and aluminum), which also includes a testing laboratory to check material thickness and surface characteristics. After passing the testing, the coil is either stored or staged for blanking. The blanks are then transferred to the stamping press lines to form the different vehicular panels. A typical BiW consists of about 300–400 stamped pieces, however, only a few main panels affect the overall



**Figure 1.3** The different panels of the vehicle structure

geometry, fit and finish. These panels are the roof, the trunk (inner, outer, and pan), the hood (inner and outer), the under-body, the wheel-house, the body-side, A and B pillars, the floor pan, the front module (engine cradle, crush zones, shock towers), the quarter panels, and doors (inner, outer). Some of these panels are displayed in Figure 1.3.

After the stamping process, some of the panels are joined to create sub-systems in specialized cells, as in the case for the doors where their inner and outer are adhesively bonded, hemmed and spot-welded. Additional cells exist in the stamping area for other components which are then fed to the body-weld or body-shop area. The stamping process utilizes mechanical and hydraulic presses with different tonnage, accessories and dies, so it can handle different panels ranging in shape and size, from 0.1–6.5 mm in thickness and with dimensions as small as 1 x panel thickness to as large as 500 x panel thickness.

In the body-shop area, the different panels are joined to form the car shell, starting with the under-body and then the body-side (left- and right-hand) outers. The joining of such panels is first done using tack welding to hold the pieces in place, followed by permanent spot welds. A typical vehicle shell has around 5000 spot welds, achieved through robotic welders working in designated cells and programmed offline. The completed body shells will also go through a dimensional check process using laser illumination with a charged coupled devices (CCD) camera system to monitor the shell gaps, flush setting and fit. The body-weld also features metal inert gas (MIG) welding for the under-body.

The robotic welding cells are controlled and monitored through separate programmable logic controllers (PLCs) which are then connected through a main controller to enable the complete line control through a master PLC.

The completed BiW is then transferred to the paint-line. The paint booth area cleans the car shells in immersion tanks and applies a conversion coating layer (iron phosphate or zinc phosphate) followed by an electro-coat or e-coat layer. The subsequent paint layers require drying or curing, through a combination of convection and radiation-based ovens. Spray paint booths follow the immersion stages, to apply the primer, top coat and clear coat layers. Also the paint booth area features other important steps such as applying the under-body wax and sealants followed by their curing process. Inspection for paint quality in terms of thickness, color match and contaminants is also important in the paint-line. In the paint-line, the vehicles might be taken out of the overall production sequence to create color batches, thus reducing the paint color change time. However, at the end of the line, all vehicles are arranged back in sequence.

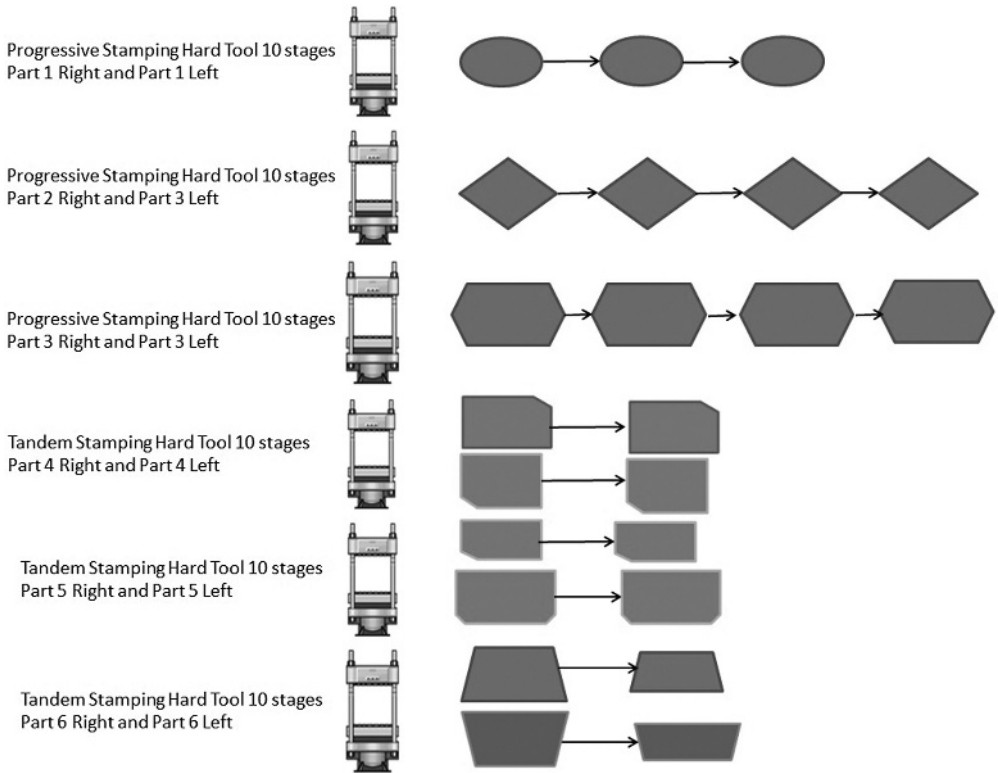
After the paint-line, vehicles are transferred to the final assembly area, where the interior (cockpit, seats, etc.) and exterior trims are installed. The final assembly area consists mainly of manual labor using power-tools and fixtures for the ergonomics, in addition to autonomous carriers that transfer the power-train components (engine, transmission, etc.) for assembly work (installing the cables, fuel hoses, and controllers) and then to the marriage area. The marriage area is where the power-train is installed in the vehicle body. The final assembly area features a variety of mechanical fastening and riveting operations to install the different trim components in the vehicle shell. Additionally, a variety of sensory systems is used to check the dimensional fit of the different components, in addition to ensuring the proper torque for each joint.

The final step in the assembly process tests the vehicle operation and build, using a chassis dynamometer and a water-test chamber.

The assembly plants require a sophisticated control system that not only monitors the different areas' performance (stamping, body-weld, paint and final assembly) but also synchronizes these activities with the reception of parts from the suppliers' network and with the power-train facility.

The flow of parts and semi-finished vehicles within an assembly plant go through different layouts within each assembly area. In the stamping area, the parts are distributed between the different stamping presses depending on the press tonnage and the dies assigned to that press. Also the staging and storing of stamped pieces are done on racks and then transferred to the body-shop or to specialized cells separately, see Figure 1.4. In other words, the layout in the stamping area is similar to a product-based layout not a process-based one. A product-based layout is similar to the ones found in small workshops or a carpenter shop, where the flow of pieces (panels) and equipment allocation (dies) changes according to the product type (vehicle type).

In the body-weld, there is a main assembly line where the sub-assemblies are fed to be joined to the main body frame. So the body-shop layout is a process-based layout, because the focus is on repeating the same process for all product (vehicle) types. The body-weld overall layout is similar to a spine, where the specialized cells that create the door sub-assemblies (joining inner and outer), the hood, the under-

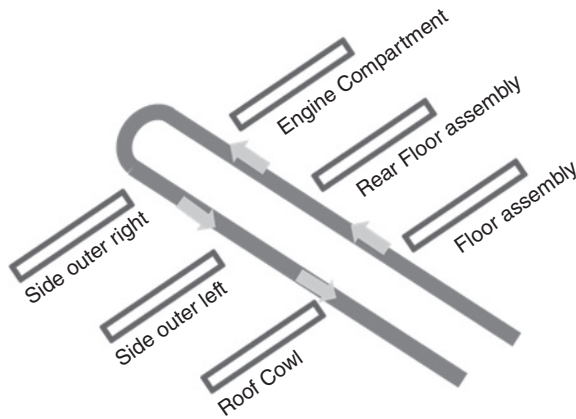


**Figure 1.4** A schematic of a typical stamping line layout

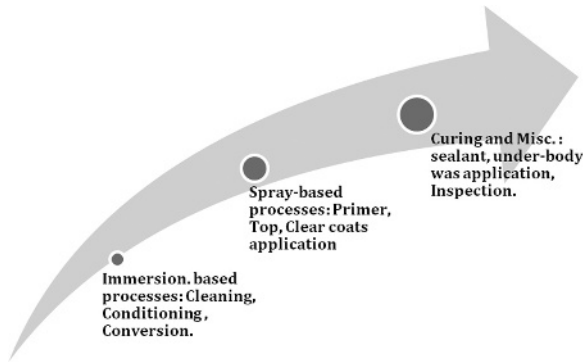
body, feed the main line that joins them to the body main shell, see Figure 1.5. The paint-line layout starts with a single straight line for the cleaning and the conditioning steps, the conversion coating (phosphate), and the e-coating immersion tanks. Then the vehicles are sent to a selectivity bank area (with a flexible conveyor system) so batches of vehicles of the same color are created for the spray booths. Some original equipment manufacturers (OEMs) like Toyota do not use the color-batching strategy but instead developed their paint-line booths to use a cartridge color system, where the robots can switch between different cartridges to change colors, thus eliminating the need to clean the paint supply line every time the color is changed. The overall flow within the paint-line is displayed in Figure 1.6, illustrating the different painting steps and layout. The final assembly area follows a process-based layout using a straight or a horseshoe-shaped assembly line.

### 1.2.2 Basics of the Power-train Processes

The power-train facilities are mainly responsible for building the vehicle power-train and drive-line components such as the engine and transmission. The power-train



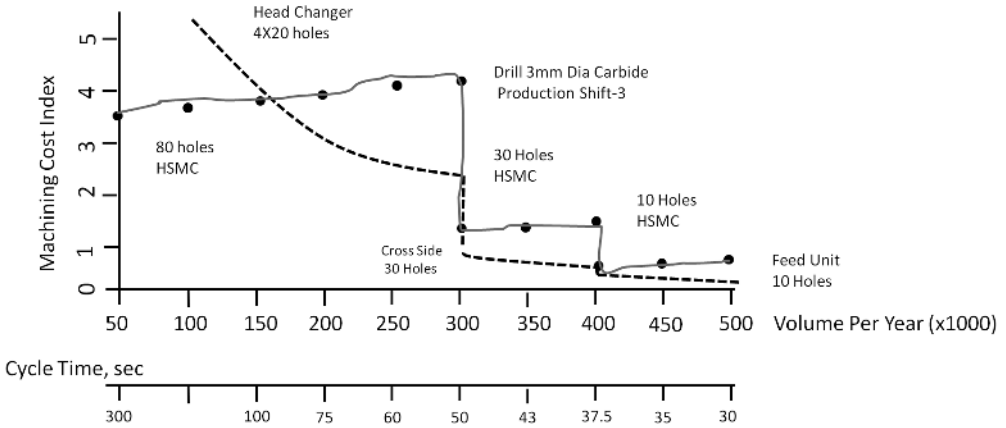
**Figure 1.5** The layout of a body-weld line



**Figure 1.6** The basic processes in an automotive paint-line

plants feature different transformational manufacturing processes from those found in the assembly plants. The power-train plants use a variety of forging, casting and machining operations to fabricate the engine components and the transmission. For example, the engine cylinder blocks are made of cast iron or are cast out of aluminum or in some cases from aluminum with a magnesium core to reduce the total weight of the engine. After the entire engine and the transmission components have been manufactured, they are assembled manually. For example, after casting and machining the engine cylinder block and the exhaust manifold, forging the pistons and the crankshaft, and finishing the valves, the crankshaft is installed manually in the cylinder block and secured by the bearing caps, which are torqued automatically. Then the pistons are lubricated and installed in the cylinder block carefully to prevent scratching the cylinder lining. Then the cylinder head is mounted and torqued to hold



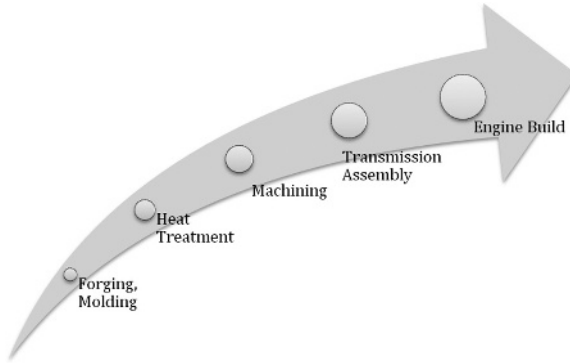


**Figure 1.7** An estimated cost comparison between the multi-spindle drilling and high speed machining centers

the valves assembly. The inlet and exhaust manifolds are installed next and fastened mechanically. The testing of the engine operation is done next, using an engine dynamometer.

The power-train plant relies mainly on in-house parts and components, in contrast to the assembly plants. However, new trends in the power-train manufacturing have reduced the number of parts manufactured in-house, so most OEMs now manufacture using basic engine components: the cylinder block and head, camshaft, crankshaft, and the connecting rods. The cylinder block goes through several machining processes that consist of rough and final millings, in addition to a variety of drilling, reaming and tapping processes. In general, a typical cylinder block will go through around 70 processes. The typical cycle time in an assembly process is around 60–80 seconds per station, however, the typical cycle time for a power-train operation is around 3 minutes, which highlights the need for advanced or improved material transfer technologies in addition to high speed machining centers and multi-spindle drilling. This fact has motivated the use of specialized tooling and fixture systems along with multi-spindle head-changer and multi-slide accessories. Additionally, the three-axis computer numerically controlled (CNC) machining centers have increased the power-train flexibility and agility. Figure 1.7 shows an estimated cost-based comparison between the high speed machining centers and the multi-spindle drilling at different vehicle production levels. Additional advances in power-train machining include the use of super-abrasive tooling for the boring, milling and honing operations. For example, the crank-boring operation used to rely on tungsten carbide tooling to achieve close tolerances in the range of 0.02mm, however, the use of a poly-crystalline diamond tool has led to better quality at higher boring speeds.

To manufacture the cylinder head, around 50 drilling operations are used to apply around 70 holes, so flexible transfer lines and cell-to-cell automation help to reduce



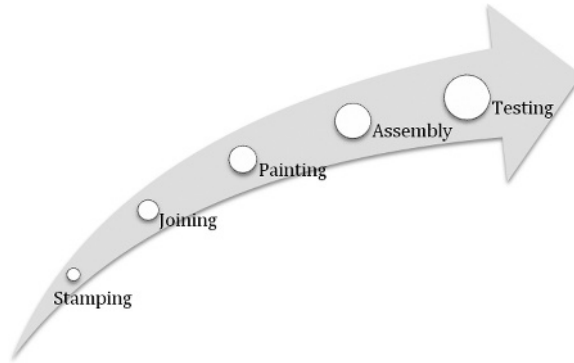
**Figure 1.8** The basic processes within a power-train facility

the cycle time. Other specialized operations like the cam boring include the use of a long-line boring bar with custom fixture, to lower or raise the cam. On the other hand, to manufacture the crankshaft, the OEMs have to apply a series of different operations with tight tolerances, that include balancing the mass of the forged steel material, turning of both edges for clamping, and turning for the main and pin bearings, drilling the oil holes, finish grinding for the main and pin bearings, then super-finish the main and pin bearings. Finally, the crankshaft is washed, balanced and inspected. The balancing is done using an intelligent fixture that rotates the shaft and compensates for any imbalances by drilling holes.

The camshaft follows a similar processing sequence to that of the crankshaft, with changes in the tooling used and with the addition of a hardening process, where the shaft is heated using induction coils, then cooled rapidly.

The power-train manufacturing processes are also responsible for making the transmission components, mainly the gear system. The typical material for the different automotive gears is based on alloyed steel that provides the hard finish for the gear teeth while the core is soft and tough, so that it resists continuous use in terms of fatigue and wear resistances. These requirements motivate the use of different heat treatment steps to achieve the hard teeth and ductile core, which include a carburizing step to increase the carbon content within a controlled depth within the gear surface, a quenching process to increase the hardness, and a tempering step to improve the core toughness.

The basic operation used to form the gear is based on hot forging, followed by variety of hobbing and shaping cutting steps to generate the gear teeth. In the shaping process, a cutting gear with the designed profile is used to generate a similar tooth profile in the blank gear, however, in the hobbing process, a worm-like cutter cuts teeth on a cylindrical blank to generate the teeth, hence the hobbing process cannot be used to generate internal gears. Other subsequent operations include gear shaving,



**Figure 1.9** The basic processes in an automotive assembly plan

where a helical gear-like cutter, with closely spaced grooves, meshes with the gear so that a controlled material is removed from the gear teeth surfaces.

The standard processes within a power-train facility are displayed in Figure 1.8. So, the overall functional look of the vehicle manufacturing processes can be shown in Figure 1.9.

### 1.3 Conclusion

The automotive manufacturing processes (assembly and power-train) play a major role in deciding on the vehicles' design characteristics and the overall cost. Thus it is very important for designers and engineers to understand the current manufacturing infrastructure available in their company's production lines. This will pinpoint the manufacturing capabilities and limitations. At the end of the day, the designer will specify the design tolerances but the machine will control the achieved tolerances. Additionally, designers should consider the materials' compatibility from the joining process welding point of view, to avoid galvanic corrosion issues.

Additionally, designers should be aware that the vehicle design complexity in terms of number of parts and intricate shapes results in additional manufacturing steps (added cost and processing time). Also, the number of robotic welders and stamping presses should be taken into account due to their direct impact on the production rate. However, one should recognize that different OEMs make their decisions with regard to the vehicle type, volume and design based on their business models, which might be based on one of the following;

1. competing based on differentiation;
2. competing based on cost; or
3. competing based on time to market.

A company competing based on different and distinguished vehicle types might add complications to their manufacturing systems to achieve new added features or provide a wide range of options. However, an OEM competing on cost aims to reduce the manufacturing cost through less complicated designs and options. The OEMs who compete based on response time typically utilize common components and designs shared between different vehicle types and between old and new models of the same vehicle type. For example, the engine cradle design can be shared between old and new models without affecting the customer's perception of the vehicle as a new model, at the same time it helps the OEM to cut the development time and cost, in addition to reducing the set-up changes in the manufacturing plants.

Additionally, recent changes in the automotive market have forced the automotive OEMs to increase their product portfolio to accommodate new demands from emerging markets, mainly in Brazil, Russia, India, and China or the BRIC countries. This increase in vehicle models has shifted the OEMs' manufacturing models from the *economy of scale* to an *economy of scope*, which motivates further understanding of the manufacturing environment because such a shift adds complications in the following areas: the sequencing of the different models, the production capacity forecasting, and parts (suppliers) and sub-systems' diversity. So new manufacturing and design strategies should be implemented and explored to alleviate some of these challenges such as the use of modular systems and subsystems between the different models, which reduce the parts' diversity and the variations within the processes. At the same time, the modularity might have negative impact on the OEMs' overall flexibility [2].

The impact of the above challenges on the automotive industry have led the automotive OEMs to revise their production and business strategies through mergers with other OEMs and by implementing efficient manufacturing procedures such as lean manufacturing and its different derivatives and versions created to suit each company style and product type. The number of automotive OEMs has dropped from 36 in 1970, to 21 in 1990, and to 14 in 2000. However, the number of automobiles produced is around 55 million vehicles [3] with the majority of production taking place in Asia (around 18 million vehicles), followed by Western Europe (17 million vehicles) and then the USA (around 11.5 million vehicles).

# Exercises

## **Problem 1**

In your own words, describe the current metrics used to judge the automobiles, by a typical customer and by an automotive engineer.

## **Problem 2**

What is the difference between the noise and vibration within the context of the automotive NVH requirement?

## **Problem 3**

Explain the three manufacturing system perspectives.

## **Problem 4**

What is the difference between the operational and strategic operations, within the procedural aspect?

## **Problem 5**

List the basic manufacturing processes involved in the making of the automobile BiW, and comment on each process layout and drivers.

## **Problem 6**

List the main differences between the automotive power-train and assembly processes, from the following perspectives: the dependence on suppliers' parts, and the nature of the processes utilized.

**Problem 7**

What is the difference between the gear hobbing and shaping processes?

**Problem 8**

What is the impact of economy of scale and the economy of scope on the automotive manufacturing process?

**Problem 9**

Automotive OEMs might compete based on different criteria, what are they?

**Problem 10**

List three challenges that have impacted the automotive industry in the past decade.