2.1 Elements of the Industrial Revolution

The Industrial revolution changed the nature of work and priorities besides the modalities of the society. The commencement of the Industrial Revolution is closely linked in fact to a small number of innovations made in the second half of the 18th century [1] such as follows-

- **Textile:** Cotton spinning using Richard Arkwright’s water frame, James Hargreaves’s Spinning Jenny, and Samuel Crompton’s Spinning Mule (a combination of the Spinning Jenny and the Water Frame) were the innovations introduced in the Textile Industry. Samuel Crompton’s Spinning Mule was patented in 1769 and came out of patent in 1783. The end of the patent was rapidly followed by the erection of many cotton mills. Similar technology was subsequently applied to spinning worsted yarn for various textiles and flax for linen.

- **Steam Power:** The improved steam engine invented by James Watt, patented in 1775 was initially primarily used for pumping out mines, but from 1780s it was applied to power machines. This enabled rapid development of efficient semi-automated factories on a previously unimaginable scale in especially over those places where water-power was not available.

- **Iron Founding:** In the Iron Industry the coke was finally applied to all stages of iron smelting replacing charcoal. This had been achieved much earlier for lead and copper as well as for producing pig iron in a blast furnace. But the second stage in the production of bar iron was depended on the use of potting and stamping (for which a patent expired in 1786) or puddling (patented by Henry Cort in 1783 and 1784).

These represented three 'leading sectors' in which key innovations profoundly affected the overall Industrial Progression, and allowed the
economic take-off by which the Industrial Revolution is usually defined. This is not to be little many other inventions, particularly in the textile industry. Without some earlier ones, such as the spinning jenny and flying shuttle in the Textile Industry and the smelting of pig iron with coke, these achievements might have been impossible. Later inventions such as the power loom and Richard Trevithick's high pressure steam engine were also vital in the growing Industrialization of Britain. The application of steam engine powering cotton mills and ironworks facilitated these to be built in places that were most convenient because other resources were available, rather than where there was water to power a watermill.

2.2 Textile Sector

In the textile sector, mills operated by steam power became the model for the organization of human labour in factories, epitomized by Cottonpolis (the name given to the vast collection of cotton mills), factories and

Fig. 2.1: Jacquard looms in the factory Gevers and Schmidt in Schmiedeberg (Deutsches Museum, Munchen)
administration offices situated in Manchester. The assembly line system greatly improved the efficiency in Textile Industry and other Industries also. With a series of men trained to do a single task on a product, then having it moved along to the next worker, the number of finished goods also augmented significantly.

Textile Industry has become highly dependent on very complex distributed systems for yarn production and as well as for cloth production. The increasingly automated systems are growing slowly beyond manageability. Many strategies and techniques, though well-founded on physics and mathematics, do not provide a system design that is correct-by-construction. To make imperfection acceptable, the involved risks in terms of cost and potential harm to others demand at least an adequate approach to prevent the worst to the largest affordable extent. The alarming observation is made that the well-founded arsenal, including rigorous exact modeling fails to bring sufficient manageability and sufficiently predictable behavior of the increasing complex manmade systems crating the goods that have become the fabric of our society [2].

Expansion of manmade systems and Industrial automation is an outcome of interaction between market-pull and technology-push. Industrial automation has a long historical evolutionary expedition starting with the advent of machines driven by windmills in the Dutch Zaanstreek in the 17th century, greater automation in the spinning and pattern weaving industry (Fig. 2.1) via the production streets popularized by Ford in the early 20th century to semi-automatically managed energy production and distribution systems. In automated processing the pursued short time-to-market and technology adaptableness incited rapid replication of errors as said by Bouyssounouse et al in [3] as "In ultra-dependable systems even a small correlation in failures of the replicated units can have a significant impact on the overall dependability". The
accumulation of such deviations resulting into a harmful failure must be prevented by a pro-active rather than a reactive attitude.

2.2.1 Loom

A loom is a device used to weave cloth. The basic purpose of any loom is to hold the warp threads under uniform tension to facilitate the interweaving of the weft threads.

![Fig. 2.2: Warp and Weft](image)

In weaving, the warp is the set of lengthwise yarns through which the weft is woven. Each individual warp thread in a fabric is called a warp end. Warp is spun fiber. The spin of the fiber can be in either an "s" twist or a "z" twist. The weft is the yarn that is woven back and forth through the warp to make cloth. When weaving on a loom, the warp yarns are placed in tension before weaving begins. The precise shape of the loom and its mechanics may vary, but the basic function remains the same. Weaving machines are classified into four groups according to their weft insertion systems as Shuttle, Projectile, Rapier, and Jet (i.e. air and water jet) looms. Of these groups, the shuttle and
projectile weft insertion systems could gain the popularity in term of their economic life, but suffers from the low weaving velocity. The water jet weft insertion system does not have a wide application in practice, as it is only suitable for yarns made of hydrophobic fiber [4].

Major classes of looms are as follows:

- A back strap loom with a shed-rod
- Warp weighted loom
- Handloom
- Power loom
- Dobby loom
- Jacquard loom
- Water-jet weaving
- Rapier weaving
- Air-Jet Weaving

Textile World presents some recent technologies that provide improved efficiencies in the weaving mill. The machinery suppliers are constantly challenged to provide up-to-date machinery using recent technologies. In times of increasing energy costs, it is of utmost interest for fabric producers to use weaving machines that offer low energy consumption.

- **Rapier weaving**

  The Rapier Weaving machines are the most flexible machines. Their application range covers a wide variety of fabric styles. A Shuttleless Weaving Loom in which the filling yarn is carried through the shed of warp yarns to the other side of the loom by fingerlike carriers called rapiers. One type has a single long rapier that reaches across the loom’s width to carry the filling to the other side. Another type has two small rapiers, one on each side. One rapier carries the filling yarn halfway through the shed, where it is met by the other rapier, which carries the filling the rest of the way across the loom.

  Rapier weaving machine comes with modern mechanics, exclusively developed to drastically reduce the vibrations thus reaching a far ahead performance compared with other weaving machines. Besides the higher speed
it offers low maintenance requirements, quick style change and lowest production cost which all contribute to increase the profitability. The typical mechanism of rapier weaving machine is shown in fig. 2.3.

![Fig. 2.3: Rapier weaving machine [5]](image)

1 Cone  
2 Metering rollers  
3 Weft preparation device  
4 Weaving rotor

- **Air-Jet Weaving**

  In this loom a jet of air carries the yarn through the shed. A shuttleless loom is capable of very high speed that uses an air jet to propel the filling yarn through the shed. Italy-based *Itema* weaving has recently upgraded its Sulzer
Textil™ L5500 air-jet weaving machine, suited primarily for applications such as quality apparel and home textile fabrics made with natural or man-made fibers or blends. Key benefits of this machine are said to be the fabric quality and low running costs. According to Itema Weaving, the L5500's strength is its competitiveness in terms of its capacity to conveniently weave fabrics that comply with superior quality standards, while also maintaining a high degree of efficiency even at top performance levels. The company adds that "conveniently" also means producing with reduced off-quality rates and reduced air consumption per meter of fabric, which enhances the profit. The L5500's RTC (Real Time Controller) function enables the machine to adapt to various weaving conditions, thereby obtaining significant air-consumption savings. Air-jet weaving systems feature the advantages like High productivity, Low investment cost, Ease of operation and Low maintenance costs.

Pile formation by air-jet mechanism is based on the principle of a stable and precise shifting of the beat-up point. Using this principle the fabric is shifted towards the reed by means of a positively controlled movement of the whip roll (Fig. 2.4, label 6) and a terry bar together with the temples on the beat-up of the fast pick. The sturdy reed drive is free of play. It provides the necessary precision for the beat-up of the group of picks. A compact, simplified whip roll system with the warp stop motions arranged on two separate levels improves handling and has a decisive influence on reducing broken ends. A drastic reduction in the number of mechanical components results substantially into a minimum maintenance. With the help of Electronics the precision of measuring the length of pile yarn gets improved leading to a better fabric quality due to constant pile height and fabric weight. The weaving process is so exact that the precise mirrored patterns are possible and velour (a plush woven fabric resembling velvet, chiefly used for soft furnishings and hats) weavers experience minimal shearing waste. The tensions of the ground and pile warps (Fig. 2.4, labels 1 and 2) are detected by force sensors (Fig. 2.4, labels 3 and 9)
and electronically regulated. In this way warp tension is kept uniform from full to the empty warp beam. To prevent starting marks or pulling back of the pile loops the pile warp tension can be reduced during machine standstill [4]. Fig. 2.4 illustrates Dornier air-jet terry weaving machine.

![Air jet weaving machine mechanism](image)

**Fig. 2.4: Air jet weaving machine mechanism [4]**

1 Ground warp  
2 Pile warp  
3 Measuring unit  
4 Terry motion cams  
5 Setting lever for terry spacing  
6 Cam driven whip roll for ground warp  
7 Precise setting for terry spacing  
8 Cloth roll  
9 Warp tension sensor

Substantial operational costs in Industrial plants are related to maintenance. In many cases, there is a lack of factual data to determine the real need for repair or maintenance of machinery, equipment and Industrial plant systems. Induction motors can be found in almost all types of applications. It is prone to many problems, such as broken bars, eccentricities, shorted windings
and bearing defects. These problems are usually detected when the machine is on the verge of breakdown status and sometimes, after irreversible damage. Condition monitoring can significantly reduce maintenance costs and the risk of unexpected failures through the early detection of potentials risks. However, there must be an adequate means of condition assessment and fault diagnosis [6].

The area of system maintenance cannot realize its full potential if it is only limited to preventive approaches. The Textile Industry Machinery includes Spinning Machine, Weaving Machine, Sizing, Combing, Warping Machine and a majority of mechanisms are exclusively run by the motor. The role of induction motor in the Textile Industry is highly significant as number of machines and variety of mechanisms are totally reliant on the good health of motor. By and large the fault diagnosis of induction motors has been concentrated on sensing failures in the stator, the rotor, bearings, and especially overload conditions. Even though mechanical sensing techniques based on thermal and vibration monitoring have been widely practiced, most of the recent research has been inclined toward electrical sensing with emphasis on analyzing the motor stator current [7].

On line fault diagnostics of induction motors are incredibly important to ensure safe operation, timely maintenance, increased operation reliability, and preventive rescue. In recent years, intensive research efforts have been focused on developing new techniques for monitoring and diagnosing electrical machines. The fault diagnosis techniques presented in [8, 9] are seem to be powerful methods for diagnosing motor faults and have recently been successfully applied to diagnosis of stator faults of large induction motor used in the Industrial field, and it has turn out to be the standard of online motor diagnosis. The main benefit of this technique is its ability to extract automatically the characteristic relative to the different machine operating modes.
2.3 Fault

The Textile Industry comprises a set of machineries encompassing huge number of components. This complicates the system reliability issues. “Reliability is the ability of a component, process or a system to perform a required function correctly under stated conditions within a given scope, during a given period of time.” The reliability is severely affected by faults and failures irrespective of anticeptional or accidental. Therefore the reliability analysis is directly concerned with the kind of faults and failures. "A fault is an unpermitted deviation of at least one characteristic property (feature) of the system from the acceptable, usual, standard condition."

Some remarks about the faults are as follows-

- A fault is a state within the system.
- The unpermitted deviation is the difference between the fault value and the violated threshold of a tolerance zone set for its usual value. [5]
- A fault is an abnormal condition that may cause a reduction in, or loss of, the capability of a functional unit to perform a required function.
- There exist many different types of faults such as design fault, manufacturing fault, assembling fault, normal operation fault (e.g. wear), wrong operation fault (e.g. overload), maintenance-fault, hardware-fault, software-fault, operator's fault. (Some of these faults are also called errors, especially if directly caused by humans).
- A fault in the system is independent of whether the system is in operation or not.
- A fault sometimes may not affect the correct functioning of a system.
- A fault may initiate a failure or a malfunctioning of the system.

A typical failure probability curve known as the ‘hazard function’ (Chestnut, 1965) is depicted in Fig.2.5. It bears a resemblance to the shape of bathtub hence called bathtub-curve. Very early during the life of a machine, the rate of failure is relatively high (so-called infant mortality failures). After all
the components settled down the failure rate relatively stays constant and then slightly goes low. Then, after the machinery or systems put on operating over a relatively longer time of operation, the failure rate again begins to increase (so-called wear out failures), until all components or devices reach to the total failure state.

2.3.1 Types of Faults

Faults are usually reciprocated in terms of emblematical behavior for the system components. They may be distinguished by their form and/or time behavior and/or extent of invading space. The nature of form can be either systematic or random. The time behavior of fault may be permanent, transient, intermittent or origin of noise or drift. The extent of faults is either local or global in respect to the fault assaulted on area.

Table 2.1 gives an overview of a variety of fault types and fault liable system components. Electronic hardware shows systematic faults if they are originated from erroneous specification or wrong design practice. Once in operation the faults in hardware components are mostly random with all kind of time behavior. The faults or blunders in software (bugs) are usually systematic,
e.g. erroneous specification, blotch in the coding, poor formulation of logic, incorrect calculation, ignorance of overflows etc. They are in general not random in nature like the faults that happen in the hardware [10].

Failure of mechanical systems can be classified into following fault prone mechanisms such as distortion (bucking, deformation), fatigue and fracture (cycle fatigue, thermal fatigue), wear (abrasive, adhesive, cavitations), or corrosion (galvanic, chemical, biological). For example the fault arise due very small changes called drift caused by wear or corrosion or abrupt changes called *distortion fracture* at any time or after prolonged stress.

**Table 2.1: Characteristics (√) of primary faults for different components**

<table>
<thead>
<tr>
<th>Types of faults</th>
<th>Component</th>
<th>Mechanical component</th>
<th>Electrical Components</th>
<th>Electronic Hardware</th>
<th>Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systematic</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Random</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Random</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time behavior</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permanent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transient</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intermittent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drift</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extent</td>
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<td></td>
</tr>
<tr>
<td>Local</td>
<td>√</td>
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<tr>
<td>Global</td>
<td></td>
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</tr>
</tbody>
</table>

Electrical systems usually consist of a large number of components with various failure modes like shortcuts, loose or broken connection, parameter changes, contact problems, contamination, EMC problems etc. Generally electrical faults appear more randomly than mechanical faults. Table 2.1 includes the effect of primary faults for the different components and their typical behavior. The extent of fault depends very much on the importance of
the components and can be global for all cases even though the faults primarily appear to be local [11].

Reliability analysis is usually based on the assumption of random faults. This is common especially for Electronic and Electrical Components. For big sized system the systematic faults which appears to be random because of large number of components comprising the system. This is holds true also for large Mechanical Systems and Software Systems.

2.3.2 Fault Models

A suitable modeling of faults is significant and helps decide the appropriate fault-detection method. A realistic approach takes for granted the understanding between the real physical faults and their consequence on the mathematical process models. This can usually only be provided by the inspection of the real process under consideration, the understanding of the physics and a fault-symptom-tree analysis. The sources of faults are ample and stem from one or the other from the following-

- Incorrect System Design,
- Wrong System Assembling,
- Erroneous Machine Operation,
- No or Untimely Maintenance,
- Inevitable Ageing,
- Slow and Imperceptible Corrosion,
- Capricious Wear during Normal Operation etc.

With regard to the operation phase the faults may already be present or they may appear suddenly with a small or large scale and in steps or gradually as in case of drift. Faults may be deterministic, however intermittent faults appears as stochastic faults [12].
2.4.2.1 Basic Faults Model

A fault can be defined as an unpermitted deviation of at least one characteristic property called feature from a usual condition. The feature can be any physical quantity. If the quantity is part of a physical law modeled in the form given by an equation (2.1) and measurements of input variable $U(t)$ and output variable $Y(t)$ are available, the feature expresses itself either as input variable $U(t)$.

$$Y(t) = g[U(t), x_i(t), \varepsilon]$$  \hspace{1cm} (2.1)

Output variable $Y(t)$, state variable $x_i(t)$ (time dependent function) or parameter $\varepsilon$ (usually constant value). Hence, faults may reciprocate in terms of either changes in signals or parameters. The time dependency of faults is shown in Fig. 2.6. This could be of one of the following types-

- Step like Abrupt Faults
- Drift-like Incipient Faults
- Interrupt causing Intermittent Faults

With regard to the corresponding signal flow diagrams (Fig. 2.7), the changes of signals are additive in nature. Because a variable $Y_u(t)$ is changed by an addition of $f(t)$

$$Y(t) = Y_u(t) + f(t)$$  \hspace{1cm} (2.2)

And the changes of parameters are multiplicative in nature. Because input variable $U(t)$ is multiplied by $f(t)$.

$$Y(t) = (u + \Delta u(t))U(t)$$

$$= u U(t) + \Delta u(t)U(t)$$

$$= Y_u(t) + f(t)U(t)$$  \hspace{1cm} (2.3)
For the additive fault the measurable change $\Delta Y(t)$ of the variable is independent on any other signal.

$$\Delta Y(t) = f(t)$$  \hspace{1cm} (2.4)

Sometimes instead of the output signal $Y(t)$, the input signal $U(t)$ or a state variable $x_i(t)$ may get altered. But for the multiplicative fault, the measurable change of the output $\Delta Y(t)$ depends on the input signal $U(t)$.

$$\Delta Y(t) = f(t)U(t)$$  \hspace{1cm} (2.5)

In other words if the signal $Y(t)$ can be measured, the additive fault is also measurable for any $Y(t)$, but multiplicative fault can be detected if $U(t) \neq 0$. The amount of the change $\Delta Y(t)$ then depends on the size of $U(t)$. 

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Chapter 2 Machine, Fault and Fault Diagnosis
2.4 Fault Diagnostic Methods

The overall concept of fault diagnosis system involves the following three essential tasks which are shown in Fig. 2.8:

- **Fault Detection**: It is a process where an abnormal operating condition is detected and reported. It simply indicates whether a fault has occurred or not. In fault detection an incidence of fault in the functional units of the process is identified that leads to an undesired or intolerable behavior of the whole system. Early detection of fault perhaps provides invaluable warning on emerging problems that could be of immense significance for initiating the appropriate actions to avoid serious process upset.
- **Fault Isolation**: It is a process that comes after the fault being detected. It is nothing but the localization and classification of faults being detected. It further
helps in determining which component and/or subsystem and/or system is on the verge or in the state of failure.

![Fault Detection (FD) - Fault Isolation (FI) - Fault Analysis (FA)](image)

**Figure 2.8: Overall Concepts of Fault Diagnosis System**

- *Fault Analysis or Identification*: Fault identification means the determination of the type, magnitude and cause of the fault being detected and isolated. It identifies cause variables most pertinent to fault based on the analysis of observations being made in the event of fault occurrence.

  A Fault Diagnosis System, depending on its performance is called FD (for Fault Detection) or FDI (for Fault Detection and Isolation) or FDIA (for Fault Detection, Isolation and Analysis) system, whose outputs corresponds to *Alarm Signals* to indicate the event of faults or *Classified Alarm Signals* to show which fault has occurred or *Data of Predefined Types* providing the information about the type and/or magnitude of the fault being detected.

### 2.4.1 Basic Maintenance Strategies

Maintenance strategies can be divided into three main groups [13]:
(1) Run-to-Failure,
(2) Scheduled, and
(3) Condition-Based Maintenance (CBM).

Although each of these strategies has distinct benefits and weaknesses, in specific circumstances one strategy looks to be more convenient and appropriate over the other. Therefore no strategy alone could be considered as always superior or inferior over the other.

1. Run-to-Failure (Breakdown) Maintenance

Run-to-failure or breakdown maintenance is a strategy where maintenance is in the form of repair work or replacement, and performed only in the event of failure of machinery. In general, run-to-failure maintenance is more appropriate when the following situations exist.

- The equipment is redundant.
- Low cost spares are available.
- The process is interruptible or there is stockpiled product.
- All known failure modes are safe.
- There is a known long mean time to failure (MTTF) or a long mean time between failures (MTBF).
- There is a low cost associated with secondary damage.
- Quick repair or replacement is possible.

An example of the application of run-to-failure maintenance can be found in the incidence of fault in the standard household light bulb. This device satisfies all the requirements above and therefore the most cost-effective maintenance strategy is to replace burnt out light bulbs as and when needed.

Fig. 2.9 shows a schematic demonstrating the relationship between a machine’s time in service, the load (or duty) placed on the machine, and the estimated remaining capacity of the machine. Whenever the estimated capacity
curve intersects with (or drops below) the load curve, the probability of failure reaches to maximum. At these time junctures, repair work must be carried out.

If the situation that exists fits within the “rules” outlined above, all associated costs (repair work and downtime) will be minimized when run-to-failure maintenance is adopted.

2. Scheduled (Preventative) Maintenance

When specific maintenance tasks are performed at set intervals of time (or duty cycles) in order to maintain a significant margin between machine capacity and actual duty, the type of maintenance is called Scheduled or Preventative Maintenance. Scheduled Maintenance is most effective under the following circumstances.

- Data describing the statistical failure rate for the machinery is available.
- The failure distribution is narrow, meaning that the MTBF is accurately predictable.
- Maintenance restores close to full integrity of the machine.
- A single known failure mode dominates.
- There is low cost associated with regular overhaul/replacement of the equipment.
• Unexpected interruptions to production are expensive and scheduled interruptions are not so bad.
• Low cost spares are available.
• Costly secondary damage from failure is likely to occur.

An example of scheduled maintenance practices can be found under the hood of a car. Oil and oil filter changed on a regular basis are part of the scheduled maintenance program that most car owners practice. A relatively small investment in time and money on a regular basis acts to reduce (but not eliminate) the likelihood of a major failure taking place. Again, this example shows how and when all or most of the criteria listed above are satisfied, the overall maintenance costs will certainly go down to minimal.

Fig. 2.10 shows a schematic demonstrating the relationship between a machine’s time in-service, the load (or duty) placed on the machine and the estimated remaining capacity of the machine when scheduled maintenance is being practiced. In this case, maintenance activities are scheduled at regular intervals in order to restore machine capacity before a failure occurs. In this way, there is always a margin between the estimated capacity and the actual load on the machine. If this margin is always present, there should theoretically never be an unexpected failure, which is the ultimate goal of scheduled maintenance.

**Fig. 2.10: Time vs. estimated capacity and actual load (Scheduled Maintenance)**
3. Condition-Based Maintenance (CBM)

Condition-Based Maintenance also called Predictive or Proactive requires some means of assessing the actual condition of the machinery in order to optimally schedule maintenance, achieve maximum production, and yet has to avoid unexpected catastrophic failures. Condition Based Maintenance should be employed when the following conditions apply.

- Expensive or critical machinery is under consideration.
- There is a long lead-time for replacement parts (no spares are readily available).
- The process is uninterruptible (both scheduled and unexpected interruptions are excessively costly).
- Equipment overhaul is expensive and requires highly trained people.
- Few highly skilled maintenance people are available.
- The costs of the monitoring program are acceptable.
- Failures may be dangerous.
- The equipment is remote or mobile.
- Failures are not indicated by degeneration of normal operating response.
- Secondary damage may be costly.

An example of Condition Based Maintenance practices can again be found in car, but out of hood, the tires. Regular inspections of the tires (air pressure checks, looking for cracks and scratches, measuring the remaining tread, listening for slippage during cornering) can all be used to make an assessment of the remaining life of the tires and also the risk of catastrophic failure. In order to minimize costs and risk, the tires are replaced before they are worn out completely, but not before they have given up the majority of their useful life. A measure of the actual condition of equipment is used to utilize maintenance resources optimally.
Fig. 2.11 shows a schematic that demonstrates the relationship between a machine’s time in service, the load (or duty) placed on the machine and the estimated remaining capacity of the machine when Condition-Based Maintenance is being practiced. Note that the margin between duty and capacity is allowed to become quite small (smaller than in scheduled maintenance), but the two lines never touch (as in run-to-failure maintenance). This results in a longer time between maintenance activities than for scheduled maintenance. Maintenance tasks are scheduled just before a failure is expected to occur, thereby optimizing the use of resources. This requires that there exists a set of accurate measures that can be used to assess the machine integrity.

Each of these maintenance strategies has its advantages and disadvantages and situations exist where one or the other is appropriate. It is the Maintenance Engineer’s role to decide on and justify the use of any one of these procedures for a machine under consideration. There are also instances where a given machine will require more than one maintenance strategy during its operational life, or perhaps even at one time and situations where more than one strategy is appropriate within a particular plant. Examples of these situations include the need for an increased frequency of monitoring as the age of a machine increases and the likelihood of failure increases, and the scheduling of maximum time between overhauls during the early stages of a
machine’s useful life, with monitoring in between looking for unexpected failures.

As shown in fig. 2.12 the main modules of CBM systems are as follows-

- Sensing and data acquisition
- Signal processing and condition monitoring
- Fault diagnosis and health assessment
- Prognosis
- Decision support and
- Presentation

Machine Diagnosis is defined as an ability to detect fault or anomaly conditions, isolate which component in the system, and decide the potential impact of a failing or failed component on the health of system. In the Industrial and Manufacturing areas, prognosis is the capability to foretell the remaining useful life (RUL) of component. The task of prognosis module is to monitor and track the time evolution of the fault. Consequently the diagnosis
and prognosis modules are gradually becoming the principal components of CBM and have to be developed with much consideration [14].

There are several benefits of implementing the CBM system in general and diagnosis/prognosis in particular such as follows-

- Reduced maintenance costs
- Increased equipment reliability
- Reduced equipment downtime
- Extended service life of the observed system
- Constant evaluation of the system condition
- Increased operational safety
- Reduced severity of faults
- Attempt towards total elimination of catastrophic failures
- Extended maintenance cycle
- Reduced technician training requirements

Due to these benefits and low maintenance cost, CBM system has become one of the popular diagnosis and maintenance system in the Industrial Sectors. Machinery fault diagnosis is a determination of a specific fault or failure that has occurred in a system, while prognosis is “estimation of time to failure and risk for one or more existing and future failure modes”. Machinery maintenance has evolved from corrective and preventive maintenance to condition-based maintenance [15].

Sandy Dunn [16] describes the significance of condition-based maintenance by identifying six business needs in 21st century, viz.

- The need to predict equipment failures
- The need for a holistic view of equipment condition
- The need for greater accuracy in failure prediction
- The need to reduce the cost of condition monitoring
- The need to improve equipment and component reliability
• The need to optimize equipment performance

Intelligent Machine Fault Diagnosis and Machine Condition Prognosis based on Adaptive Fuzzy Inference Systems were initially introduced by Jang [17] and Breiman et al [18] respectively.

2.4.2 Fault Detection Methods (FDM)

Fault detection methods are mainly classified into two categories as follows-

1. Detection with single signals and
2. Detection with multiple signals and models [19].

FDM are shown in figure 2.13. The most simple and frequently used method for fault detection is the limit checking of a directly measured variable $Y(t)$. The measured variables of a process are monitored and checked if their absolute values or trends exceed certain thresholds. A further possibility is to check their plausibility.

Many measured signals of processes show oscillations that are either of harmonic or stochastic nature or both. If changes of these signals are related to faults in the actuators, the process and sensors then the Signal Model-Based Fault-Detection Methods can be applied. Especially for machine vibration, the measurement of position, speed or acceleration allows to detect, for example, imbalance or bearing faults, knocking, chattering etc. But also from many other sensors like electrical current, position, speed, force, flow and pressure contain frequently oscillations with a variety of higher frequencies than the process dynamics.

Model-based methods of fault detection use the relations between several measured variables to extract information on possible changes caused by faults. The associations among the measured variables are mostly analytical relations in the form of process model equations, but can also be causalities in form of If-Then rules.
For large scale processes such as chemical plants, the development of model based fault detection methods requires considerable and eventually too high endeavor. In such cases Data Driven Analysis Methods offer an

**Fig. 2.13: Fault Detection methods**
alternative way. These methods are attractive where the available process measurements are highly correlated and a small number of events (faults) produce unusual patterns [20]. When the process data are highly correlated, the original process data can be projected onto a smaller number of principal components or latent variables thereby reducing the dimension of the variables. The Principal Component Analysis (PCA) models are basically linear and static, and are developed from a process in normal operation. However, they can be extended to other situations too.

**2.4.3 Fault Diagnosis Methods**

The Fault Diagnosis task consists of the determination of the fault type with as many details as possible including the fault size, location of the fault etc. The diagnostics procedure is based on the observed analytical and heuristic symptoms besides the heuristic knowledge of the process. Fig. 2.14 summaries the single steps as well as automatically measured variables similar to the human observe the variables. In both the cases the feature extraction and the detection of changes in normal or nominal situation are performed. Analytical and heuristic symptoms must then be brought in a unified symptom

![General Scheme for Fault Detection and Fault Diagnosis](image)

**Fig. 2.14: General Scheme for Fault Detection and Fault Diagnosis**
representation in order to accomplish the diagnosis.

Features are extracted values from signal or process models describing the status of the process (e.g. parameters, state variables, parity equation error etc) and the symptoms are unusual changes of the features from its normal or nominal values. In a fault-free case the symptoms are zero. All available symptoms as facts and the fault-relevant knowledge about the process form the inputs to the knowledge-based diagnosis procedure. The different classes of symptoms are as follows-

a) **Analytical Symptoms**

The analytical symptoms ($S_{ai}$) are the consequences of the limit checking of measurable signals, signal or process-model Fault-Detection Methods and of Change-Detection Methods.

b) **Heuristic Symptoms**

Heuristic symptoms ($S_{hi}$) are the observations by the operating personnel in the form of acoustic noise, oscillations or optical impressions like colors or smoke. These empirical facts can usually only be represented in form of qualitative measures, e.g. as linguistic expressions like "little", "medium" or "much".

c) **Process History and Fault Statistics**

A third category of facts depends on the general status based on the history (past life) of the process. The process history includes the past information of running time, load dealings, instant of last maintenance or repair. If fault statistics exist, they describe the frequency of certain faults for the same or similar processes. Depending on the quality of these measures, they can be used as analytical or heuristic symptoms. However, the information on the process history in general is vague, and their facts have to be treated as heuristic symptoms. The knowledge about the symptoms can be represented, e.g. in the form of data strings and can include number, name, numerical value,
reference value, calculated confidence or membership value, time of detection, explanatory text etc [21].

d) Unified Symptom Representation

For the processing of all symptoms in the inference mechanism, it is advantageous to use a unified representation. One possibility is to present the analytic and heuristic symptoms \( S_i \) with confidence number \( c(S_i) \) such that \( 0 \leq c(S_i) \leq 1 \) and treatment in the sense of probabilistic approaches founded on the reliability theory. Another possibility is the representation as fuzzy set membership functions \( \mu(S_i) \) with \( 0 \leq c(S_i) \leq 1 \) [16].

By concept of membership functions, all analytic and heuristic symptoms can be represented in a unified way within the range \( 0 \leq c(S_i) \leq 1 \). These integrated symptom representations then form the inputs for the diagnosis procedure.

e) Fault-Symptom Relationships

The propagation of faults to observable symptoms follows in general a physical cause-effect relationship. Fig. 2.15 (a) shows that a fault in general influences the measurable or observable symptoms via events as an intermediate steps, both the event and the symptom being the internal physical properties. The underlying physical laws however are mostly not known in analytical form, or too complicated for calculations. The Fault Diagnosis proceeds in the backward way. It has to conclude from the observed symptoms to the faults as depicted in Fig. 2.15 (b). This implies the inversion of the causality. One cannot expect to reconstruct the fault-symptom chains solely from measured data, because the causality is not reversible or the reversibility tends to be ambiguous [22]. The intermediate events between faults and symptoms are not always visible from the symptoms behavior. Therefore, the structured knowledge has to be referred to, incurred from the inspection of the faulty behavior of process.
If no information is available on the fault-symptom causalities, experimentally trained classification methods can be applied for Fault Diagnosis. This leads to an unstructured knowledge base. If the fault symptom causalities can be expressed in the form of If-Then rules then Reasoning or Inference methods become feasible.

The fig. 2.16 gives the fault diagnosis methods. The two main methods are as follows -

1. Classification Method
2. Inference Method
The classification methods are nevertheless common for fault diagnosis applications. If no structural knowledge is available for the relation between the symptoms and the faults, the classification or pattern recognition methods can be good alternative. From statistical classification the most well-known classification scheme is given by the so-called Bayes classification. The

Fig. 2.16: Fault Diagnosis Methods
approach is based on reasonable assumptions about the statistical distribution of the symptoms.

Different types of decision trees that have originated from the social sciences are used to classify the data. Similar approaches are also common in the classification of botanical species. The system basically relies upon a series of questions that have to be answered and depending on the answer the next question narrows the species more and more until the exact plant being determined. Typical for biological problems are binary features that can be answered without ambiguity. The collection of all questions forms the complete decision tree.

For the rule-based fault diagnosis of continuous processes with unremitting variable symptoms, methods of Approximate Reasoning are more appropriate than binary decisions. The fuzzy If-Then rule expresses a fuzzy

![Diagram](image_url)

Fig. 2.17: Signal flow of fault detection, fault diagnosis and fault management
implication mapping between the fuzzy sets of the premise and the fuzzy sets of the conclusion. If the rule is interpreted by the Mamdani’s implication then compositional rule of inference offers good alternative [23].

2.5 Sensors and Sensing Strategies

Sensors and sensing strategies constitute the foundational basis for Fault Diagnosis System. Strategic issues arising with sensor suite employed to collect data that eventually will lead to online realization of diagnostic algorithms are associated with the type, quantity and location of sensors; their size, weight, cost, dynamic range, and other characteristic properties regardless of wired or wireless variety. Data collected by transducing devices are rarely useful in their raw form. Such data must be processed appropriately so that useful information may be extracted that is a reduced version of the original data but preserves as much as possible those characteristic features or fault indicators that are indicative of the fault events. Thus such data must be preprocessed in order to remove artifacts and reduce noise levels and the volume of information to be referred to subsequently. Furthermore, the sensor providing the data must be validated for not having subjected themselves to faulty conditions [24].

Once the preprocessing module confirms that the sensor data are “clean” and formatted appropriately and features or signatures of normal or faulty conditions must be extracted. This is the most significant step in the Condition Based Maintenance (CBM) architecture whose output will set the juncture for accurate and timely diagnosis of fault modes [25]. The extracted-feature vector will serve as one of the essential inputs to Fault Diagnostic Algorithms. Sensor suites are specific to the application domain, and they are intended to monitor such typical state awareness variables as temperature, pressure, humidity, speed, vibrations etc.
The typical sensors employed in the Fault Detection Process are described in the following sections.

2.5.1 Current Transformer (CT)

The standard for precise current measurement in instrumentation and other high reliability equipment applications has been the Current Sense Transformer. They are accurate, easy to implement and reliable under harsh environmental and thermal conditions. Current transformer is the most common solutions for measuring high current. CTs are also used for electrical measuring instruments and/or electrical protective devices. With CT sensor it is far convenient to reduce the line current to a value which is suitable for standard voltage levels in measuring instruments, relays etc.

Ring type current transformer as a current sensor is highly suitable for detecting the conditions of current short circuit, overload, unbalanced input for induction motor detected based on the magnitude and trend offered by the CT Sensor [26].

2.5.2 Temperature sensor

Different sensing technologies are available for temperature sensing. Besides commonly used temperature sensors, the sensors based on newest technology- Integrated Silicon Based Sensors are becoming popular. There are other sensing technologies, such as Infrared (Pyrometers) and Thermal Pile. Each of these sensor technologies cater to specific temperature ranges and environmental conditions. The sensor’s temperature range, ruggedness, and sensitivity are just a few characteristics that are used to determine whether or not the sensor device will satisfy the requirements of the target application. No single temperature sensor is ideal for all applications. The thermocouple's wide temperature range is unrivaled with the excellent linearity of the RTD and the accuracy of the Thermistor.
The Integrated Circuit Temperature Sensors offer another alternative to solving temperature measurement problems. The advantages of integrated circuit silicon temperature sensors include, user friendly output formats and ease of installation in the PCB assembly environment. Since the silicon temperature sensor is an integrated circuit, integrated circuit designs can be easily implemented on the same silicon as the sensor. This advantage allows the placement of the most challenging portions of the sensor signal conditioning path to be included in the IC chip. Consequently, the output signals from the sensor, such as large signal voltages, current, or digital words are easily interfaced with other elements of the circuit. As a matter of fact, some integrated silicon sensors include extensive signal processing circuitry providing a digital I/O interface for the microcontroller.

On the other hand, the accuracy and temperature range of this sensor does not match the other types of sensors. A temperature sensor IC can operate over a nominal temperature range of –55 to 150 °C. Some devices go beyond this range, while others operate over a narrower range. But for induction motor and Textile environment condition point of view LM35 temperature sensor being more suitable candidate has been selected in present sensing system. The LM35 is precision integrated-circuit temperature sensors, whose output voltage is linearly proportional to the Celsius (Centigrade) temperature. The LM35 thus has an advantage over linear temperature sensors calibrated in °Kelvin, as the user is not required to subtract a large constant voltage from its output to obtain convenient Centigrade scaling. It can be used with single power supplies, or with dual supplies. As it draws only 60 µA from its supply, it has very low self-heating, less than 0.1 °C in still air [27].

The over temperature range recommended for induction motor is around 45°C. With the help of LM35 temperature sensor overheat can be easily detected. The temperature parameter affects the quality of yarn and ultimately
the cloth. Therefore temperature sensing and subsequently the environment temperature monitoring in textile industry is of imperative significance.

2.5.3 Humidity Sensor

Relative humidity is a term used to describe the amount of water vapor that exists in a gaseous mixture of air. Humidity control is a big challenge in the Textile Industry.

The *sling psychrometer* is still one of the most accurate methods for determining relative humidity. This device uses two thermometers, one with a wick contained in a holder that can be swung like a fan. Wetting the wick with water and rotating the thermometers for about a minute will give the wet-bulb and dry-bulb temperatures [28]. After subtracting the wet-bulb temperature from the dry-bulb temperature to get the depression, the relative humidity can be determined. The other electronic sensors are now available in the markets which are based on the capacitive measurement principle. They are relatively cheap and easy to install and maintain than the wet bulb method. The only trouble with these electronic sensors is that they need frequent recalibration at least once in six months as they get deteriorated due rough conditions in the textile industry [29].

Two humidity sensors SY-HS220 and SHT11 were investigated for cost effectiveness and easily availability. SY-HS220 [30] is humidity sensor with the analog output and has to be connected to the A/D convertor bit of the microcontroller with intermediate stage of Op-Amp buffer to avoid loading of the microcontroller port. Operates at 5V with the minimal current consumption less than 3.0 mA and sensing range spreads over 30% to 90% of relative humidity with 5% of accuracy. The humidity sensor module comes with temperature compensation circuit with internal linearly calibrated output in the form of voltage. The other option was the digital humidity sensor SHT11 from “Sensirion”. The SHT11 is a single chip relative humidity and temperature
multi sensor module comprising a calibrated digital output. The device includes a capacitive polymer sensing element for relative humidity and a band gap temperature sensor. Both are seamlessly coupled to a 14-bit analog to digital converter and a serial interface circuit on the same chip. This guarantees the superior signal quality, a fast response time and insensitivity to external disturbances (EMC). The SHT11 has solid features over the SY-HS-220 and will be the first choice for any system developer. However it is costly and not available easily in the market hence we relied on SY-HS-220.

2.5.4 Optical Sensor/Proximity Sensor

Warping [31] is aimed at preparing the weaver’s beam to be set up on the weaving machine. Moreover the warper systems are equipped with yarn breakage monitoring systems with optical sensor as shown in fig. 2.18. During warping the thread supports the drop pin and the light beam is not interrupted (Fig. 2.18a). At thread breaking or marked thread loosening, the drop pin, being no longer supported hence rotates and shades the light beam (Fig. 2.18b). The idle threads are cut by pushing the relevant keys: the drop pins take up a position which does not interrupt the light beam, thus enabling the working of all other threads (Fig. 2.18c).

2.5.5 Pressure Sensor

Pressure measurement devices can be classified into two groups: those where pressure is the only source of power and those that require electrical excitation. The mechanical style devices that are only excited by pressure, such as bellows, diaphragms, bourdons, tubes or manometers, are usually suitable for purely mechanical systems. With these devices a change in pressure will initiate a mechanical reaction, such as a change in the position of mechanical arm or the level of liquid in a tube. While electrically excited pressure sensors are most synergistic with the microcontroller environment. These include
piezoresistive, Linear Variable Differential Transformer (LVDT), Capacitive sensors etc. Amongst these the Piezoresistive sensor is widely used.

The Piezoresistive is a solid state-monolithic sensor that is fabricated using silicon processing. Since Piezoresistive pressure sensors are fabricated on a wafer, 300 to 500 sensors can be produced per wafer and hence available on the market at a reduced cost as compared to mechanical sensors. These Piezoresistive Silicon Pressure Transmitters are produced on the new KELLER [32] automatic brazing lines on mass production of high quality pressure transmitters that too at low cost. This new technology allows the burst-free construction of the pressure port without using seals or O-rings. In the brass
sensor line (Series 21 MC) a steel insert and a nickel diaphragm is brazed into the brass housing. The main features are as follows -

- Suitable for Industrial applications
- Pressure range up to 5 Bars
- Max overload pressure range of 10 Bars
- Output is 4-20 mA
- Good operating temperature of -25 to 80 °C
- Accuracy of 1% at full scale

2.5.6 Oil Level Sensor

The oil level sensor unit is nothing but a variable resistor. The sensor unit is positioned in the oil tank of the machine. It consists of a float, usually made of foam, connected to a thin, metal rod. The end of the rod is mounted to a variable resistor. In an oil tank, the variable resistor consists of a strip of

![Figure 2.19: Float Level Sensor](image-url)
A resistive material connected on one side to the ground. A wiper connected to the gauge slides along this strip of material conducting the current from the gauge to the resistor. The wiper slides up or down with the oil level in the tank rising or falling respectively. The typical float level sensor is shown in fig. 2.19. The sensor unit operating nominally between $0 \, \Omega$ and $100 \, \Omega$ corresponding to tank being Full or Empty. There are several ways of capturing signal from sensor unit and convert it into an equivalent digital code. With one approach, the small signal from sensor is amplified and converted into digital code. When the resistance is at a certain point, it will also turn on a "Low Fuel" indicator. When the tank level reaches to its top limit the maximum current flows and the display unit indicates a “Full Fuel”.

2.6 References


