
2.1 Objects of Technical Diagnostics

The objects of technical diagnostics can be illustrated by the life cycle of all man-made technical items: from raw materials to engineering materials and—via design and production—to structures and systems, and finally, to deposition or recycling, see Fig. 2.1.

Technical diagnostics can be applied in almost all areas of technology and industry in order to ensure product quality, economical and efficient processes and, most importantly, to assure safety and reliability. In this section, the objects of technical diagnostics—engineering materials, structures and systems—are considered in brief.

2.1.1 Engineering Materials

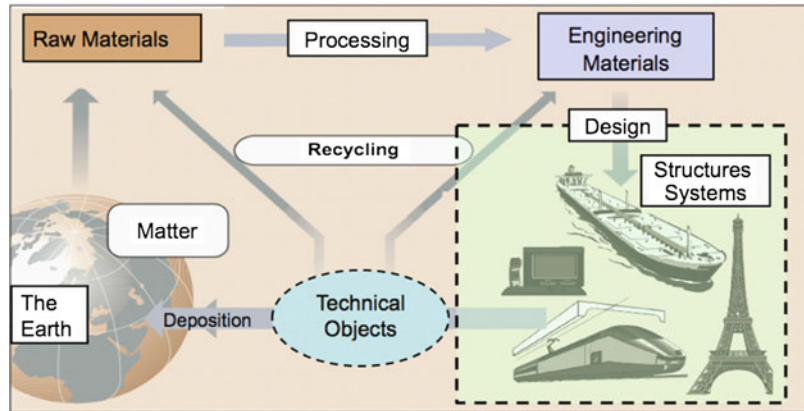
It has been estimated that there are between 40,000 and 80,000 materials which are used or can be used in today's technology [1], they can be categorized as follows [2]:

- **Natural Materials:** Natural materials used in engineering applications are classified into natural materials of mineral origin, e.g. marble, granite, sandstone, mica, sapphire, ruby, diamond, and those of organic origin, e.g. timber, India rubber, natural fibres, like cotton and wool. The properties of natural materials of mineral origin, as for example high hardness and good chemical durability, are determined by strong covalent and ionic bonds between their atomic or molecular constituents and stable crystal structures. Natural materials of organic origin often possess complex structures with direction-dependent properties. Advantageous application aspects of natural materials are recycling and sustainability.
- **Metallic Materials:** In metals, the grains as the buildings blocks are held together by the electron gas. The free valence electrons of the electron gas account for the high electrical and thermal conductivity, and the optical gloss of metals. The metallic bonding—seen as interaction between the total of atomic nuclei and the electron gas—is not significantly influenced by a displacement of atoms. This is the reason for the good ductility and formability of metals. Metals and metallic alloys are the most important group of the so-called *structural materials* whose special features for engineering applications are their mechanical properties, e.g. strength and toughness.

This chapter considers the objects of technical diagnostics and explains *Systems Thinking* as generic concept for the application of technical diagnostics in technology and industry.

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Fig. 2.1 The product cycle of technical items and the potential of technical diagnostics



- Semiconductors have an intermediate position between metals and inorganic non-metallic materials. Their most important representatives are the elements silicon and germanium, possessing covalent bonding and diamond structure and the similarly structured III-V-compounds, like gallium arsenide (GaAs). Being electric non-conductors at absolute zero temperature, semiconductors can be made conductive through thermal energy input or atomic doping which leads to the creation of free electrons contributing to electrical conductivity. Semiconductors are important *functional materials* for electronic components and applications.
- Inorganic Non-metallic Materials: The atoms of these materials are held together by covalent and ionic bonding. As covalent and ionic bonding energies are much higher than metallic bonds, inorganic non-metallic materials, like ceramics have high hardness and high melting temperatures. These materials are basically brittle and not ductile. Because of missing free valence electrons, inorganic non-metallic materials are poor conductors for electricity and heat, this qualifies them as good insulators in engineering applications. Concrete, the worlds most used construction material, is a mixture of coarse aggregates (stone or brick chips) and fine aggregates (generally sand) with a binder material (usually cement), mixed with a small amount of water. Concrete has high compression strength, but tension (e.g., due to bending) will break the microscopic rigid lattice, resulting in cracking and separation of the concrete. Thus non-reinforced concrete must be well supported to prevent the development of tension.
- Organic Materials: Organic materials whose technologically most important representatives are the polymers, consist of macromolecules containing carbon (C) covalently bonded with itself and with elements of low atom numbers (e.g. H, N, O, S). Intimate mechanical mixtures of several polymers are called blends. In thermoplastic materials, the molecular chains have long linear structures and are held together by (weak) intermolecular (van der Waals) bonds, leading to low melting temperatures. In thermosetting materials the chains are connected in a network structure and do not melt. Amorphous polymer structures (e.g. polystyrene PS) are transparent, whereas the crystalline polymers are translucent to opaque. The low density of polymers gives them a good strength-to-weight ratio and makes them competitive with metals in structural engineering applications.
- Composites are combinations of materials assembled together to obtain properties superior to those of their single constituents. A classic composite material is reinforced concrete, in which reinforcement grids, plates or fibers have been incorporated to strengthen the concrete in tension. Composites are classified according to the nature of their matrix: metal, ceramic or polymer matrix composites,

often designated as MMCs, CMCs and PMCs, respectively. Glass fiber and Carbon fiber reinforced composites are denoted GFC and CFC. The potential for a synergy of the composite constituents is one reason for the interest in composites for high-performance applications. However, because manufacturing of composites involves many steps and is labour intensive, composites may be too expensive to compete with metals and polymers, even if their properties are superior. In high-tech applications of advanced composites it should also be borne in mind that they are usually difficult to recycle.

Materials result from the processing and synthesis of matter, based on chemistry, solid state and surface physics. The microstructure of materials resulting from processing and synthesis contains

- Grains: crystallites made up of identical unit cells repeated in space, separated by grain boundaries.

- Phases: homogeneous aggregations of matter with respect to chemical composition and uniform crystal structure: grains composed of the same unit cells are the same phase.
- Lattice defects: deviations of an ideal crystal structure:
 - Point defects or missing atoms: vacancies, interstitial or substituted atoms
 - Line defects or rows of missing atoms: dislocations
 - Area defects: grain boundaries, phase boundaries, twins
 - Volume defects: cavities, precipitates.

Figure 2.2 illustrates schematically the microstructure of materials for the example of metals and alloys.

Whenever a material is being created, developed, or produced the properties the material exhibits are of central concern. Experience shows that the properties and performance associated with a material are intimately related to its composition and structure at all scale levels, but

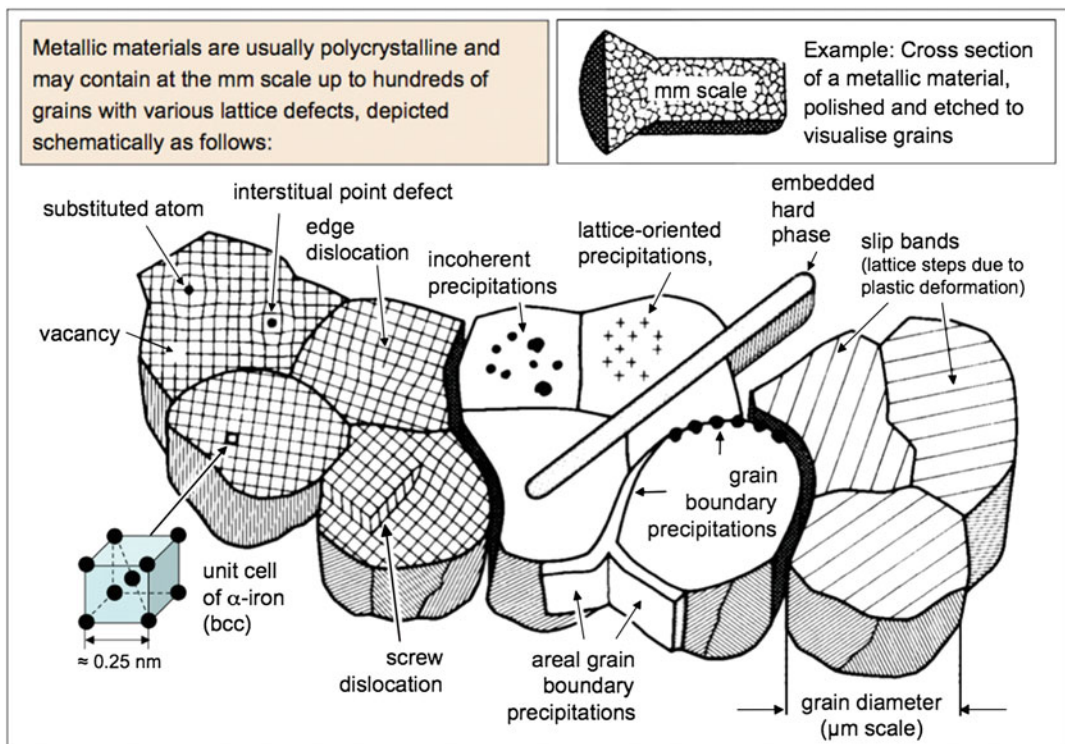


Fig. 2.2 Schematic overview on the microstructural features of metallic materials and alloys

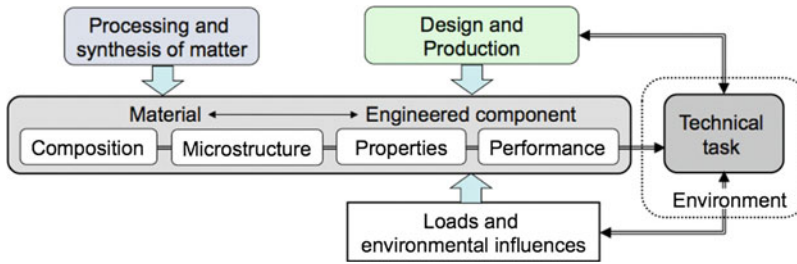


Fig. 2.3 Basic aspects of engineered materials

are also influenced by design and production. The production technologies can cause “production-induced defects” in the microstructure of materials, for example gas holes, inclusions, quenching cracks, flaws caused by welding, etc. The final material, as constituent of an engineered component, must perform under working loads and environmental influences a required task and must do so in an economical and societal acceptable manner. An overview of the basic aspects of engineered materials and engineered components is given in Fig. 2.3.

Engineering materials can be categorised in terms of their application-relevant properties in three basic groups:

- *Structural materials* have specific mechanical or thermal properties for mechanical or thermal tasks in engineering structures.
- *Functional materials* have specific electromagnetic or optical properties for electrical, magnetic, or optical tasks in engineering functions.
- *Smart materials* are engineered materials with intrinsic or embedded sensor and actuator functions, which are able to accommodate materials in response to external loading, with the aim of optimising material behaviour according to given requirements for materials performance.

Figure 2.4 gives an overview on the broad numerical spectra of some application-relevant mechanical, electrical and thermal properties of metals, inorganics and organics.

For structural materials, the combination of elasticity, strength and weight is of paramount importance in the selection of materials for engineering applications. Figure 2.5 shows a

map with strength-weight domains for the main classes of engineering materials.

2.1.2 Technical Items: Structures and Systems

The behaviour of technical items related to use is called *performance*. In structural engineering it is the ability of a product (e. g. a building as a whole or any part of it) to support or to resist loads. In machinery it is the capability of a machine, defined by one or more characteristic quantities such as power, speed, flow, or efficiency. Faults and failures occur in service. The operating parameters and influencing environmental factors on a technical item in a given application stem from its functional tasks and are borne by its structural design. The materials of a technical item are subject to mechanical and thermal working stresses, generally called “loads”, meaning any physical process acting on the component, for example mechanical stress, voltage, or temperature. The materials are also in contact with other solids, aggressive gases, liquids or biological species and they always interact with their environment. All these influences can affect materials integrity. The useful properties of the materials, of which technical items are composed, are generally responses to the stimuli of the application conditions. The stimuli loads and environmental conditions must be completely specified in order to develop a reproducible response, and to obtain reliable characteristics and data.

The general term “system” is used in the various areas of technology and industry with

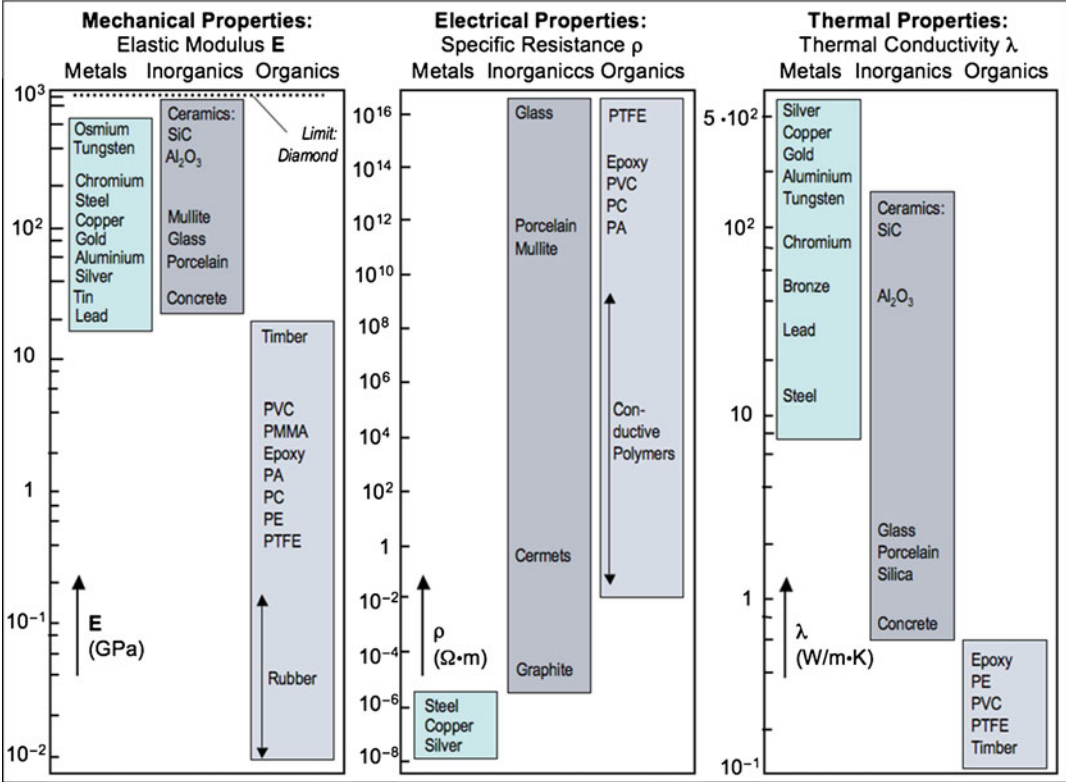


Fig. 2.4 Data of mechanical, electrical, and thermal properties for the basic types of material

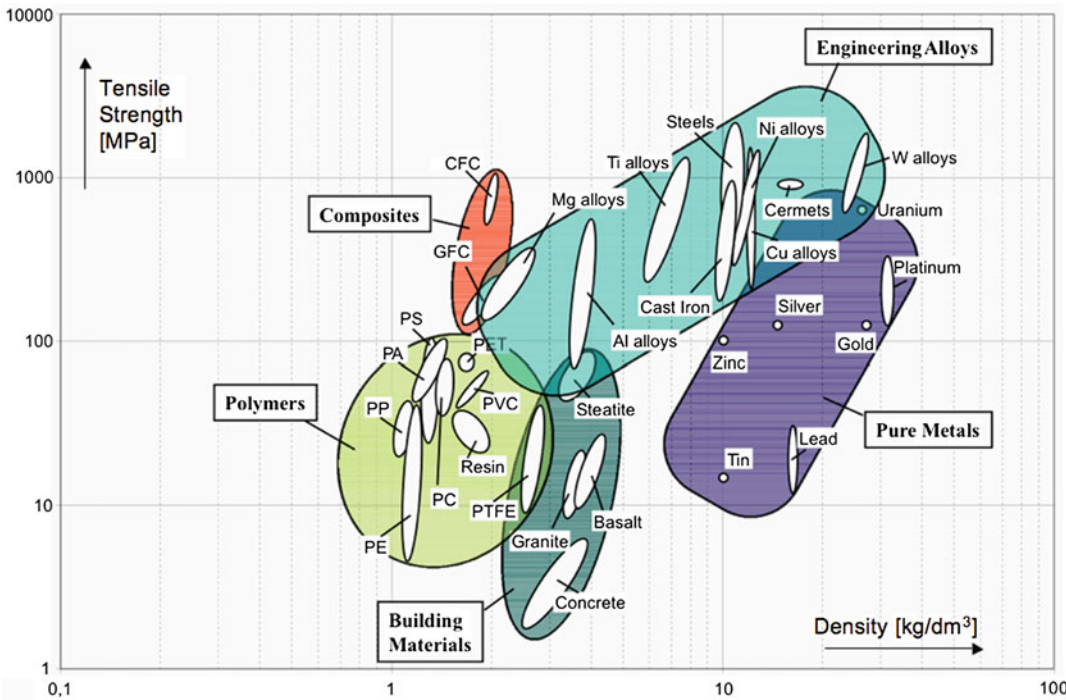


Fig. 2.5 Strength-weight map of engineering materials

somewhat different phrasing. According to International Standards [3], a system can be:

- Collection of real-world items organised for a given purpose. A system is characterized by its structure and its behaviour
 - industrial automation systems (ISO 15704).
- Set of interdependent elements constituted to achieve a given objective by performing a specified function
 - internal combustion engines (ISO 7967).
- Assemblage of components performing a specific function with associated sensors, actuators and interconnections
 - road vehicles (ISO 9141).
- Integral part of a nuclear power unit comprising electrical, electronic, or mechanical components (or combinations of them) that may be operated as a separate entity to perform a particular process function
 - nuclear power plants (ISO 6527).
- Arrangement of interconnected components which transmits and controls fluid power energy
 - hydraulic fluid power (ISO 4413).
- Assembled section of piping consisting of a representative range of pipes, fittings, connections, attachments, supports, penetrations and associated coatings
 - petroleum and natural gas industries (ISO 14692).
- Those parts of an installation that, together with the pump, determine the functional performance of the installation
 - liquid pumps and installation (ISO 17769).
- Set of interdependent items constituted to achieve a given objective by performing a specified function
 - space systems (ISO 16091).
- Delimited group of interrelated, interdependent or interacting objects that is assessed for a potential risk
 - bases for design of structures (ISO 13824).

This collection of definitions shows that different wording is used to define the various “industrial systems”. Thus, the *General System Theory* has to be considered as a generic base for a methodology of technical diagnostics that can be applied to structures, systems, and components in all areas of technology and industry.

2.2 The System Concept

The classical method of scientifically analyzing problems is “analytical reductionism”. An entity, i. e. the object of an investigation, could be broken down into its individual Parts so that each Part could be analyzed separately, and the dissections could be added to describe the totality of the entity. This basic principle of “scientific reductionism” can be applied analytically in a variety of directions, e. g. resolution of causal relations into separate Parts, searching for “atomic units” in science or for “material constants” in engineering.

Application of the classical analytical procedure depends on the condition that interactions between the Parts are non-existent or, at least, weak enough to be neglected for certain research purposes. Only under these conditions can the Parts be singled out and described mathematically. An equation describing the behaviour of the Whole is assumed to have the same form as the equations describing the behaviour of the Parts, and that partial processes can be linearly superimposed to obtain the total process.

These conditions are not met in a “System”, it consist of “Parts in interaction” forming an entity of “organized complexity” [4]. Systems thinking focuses on how the thing being studied interacts with the other constituents of the system—a set of elements that interact to produce behaviour—of which it is a part [5].

2.2.1 Principles of General System Theory

System definition: A system is a set of elements interconnected by *structure* and *function*.

1. Systems Structure

The structure of a system is given by

A the set of the elements (components) a_i , separated from the environment by a hypothetical envelope enclosing the elements, $A = \{a_1, a_2, \dots, a_n\}$,

P the relevant (materials) properties of the elements, $P = \{P(a_i)\}$, $i = 1 \dots n$,

R the relations (interactions) between the elements, $R = \{R(a_i \leftrightarrow a_j)\}$, $i, j = 1 \dots n, j \neq i$.

The normal (nominal) structure of a system is represented by the set $S_0 = \{A, P, R\}$.

If the structure of a system changes with time t , for example due to detrimental changes of element properties (P) or relations (R) under working loads L (e. g. force, temperature), the structure of a system is load and time dependent and is represented by the set $S(t, L) = \{A, P(t, L), R(t, L)\}$.

2. Systems Inputs and Outputs

The connections between the structure and its environment—crossing the hypothetical envelope enclosing the structural elements—are classified as

Inputs $\{X\}$: Operating inputs, working loads, auxiliary inputs, disturbances

Outputs $\{Y\}$: Functional outputs, loss outputs, noise, wear debris

All inputs and outputs can be categorized to belong to the cybernetic categories of *energy*, *matter*, *information*.

3. Systems Function

Basic functions of (technical) systems are:

- Support of (working) loads,
- Transfer or transformation of operating inputs into functional outputs.

The function of a system -is borne by the systems structure. The support of loads requires appropriate (load-bearing) properties (P) of the relevant systems element. The transfer or transformation of operating inputs into functional outputs (T) requires appropriate interactions (R) between relevant systems elements to enable the pertinent function.

The behaviour of a system is the manner in which the whole or part of a system acts and reacts to perform a function; it can be categorized in different states:

(a) Steady state

If the inputs and outputs are stationary and the structure of the system is stable, the functional outputs $\{Y\}$ may be describable as functions of the operating inputs $\{X\}$ through an algebraic representation of the transfer function (T).

(b) Dynamic state

If the inputs and outputs vary with time, the system is said to be in a “dynamic state”. Functional

input–output relations of a dynamic system can be often represented by differential equations. (Well-known mathematic modelling examples for mechanical systems with stable structures are differential equations with mass-spring-damper characteristics of the systems elements).

(c) Stochastic processes

In real systems, the functional input–output relations may be influenced by stochastic processes, i. e. dynamic effects of uncertainty and random disturbances (“noise”). In addition, the systems structure S_0 may be time-dependent due to detrimental changes of systems elements properties P or interactions R , i. e. $S_0 \rightarrow S = \{A, P(t), R(t)\}$. In such cases, an estimate of the limits of proper systems behaviour by means of the theory of probabilities may be attempted.

In characterizing the behaviour of systems by the terms “structure” and “function” these terms should not be isolated from each other because structure and function of systems are interconnected. A summarizing overview of the system concept is given in Fig. 2.6.

2.2.2 Application of the System Concept to the Description of Technical Items

The application of the system concept to the characterization of technical items is exemplified in Fig. 2.7 for the simplest case of “2-body systems”, namely a mechanical gear pair and an electrical transformer,

The function of both systems illustrated in Fig. 2.7 is to transfer operating inputs—speed and torque in the mechanical system and voltage and current in the electrical system—into functional outputs for the intended technical purpose. In both systems, input energy is dissipated due to friction or eddy current effects, and the ratio between the useful output and the input is the energy conversion efficiency. Regarding the structures of the systems, a fundamental difference between the electrical and the mechanical system has to be noted [6]:

- In the electrical system, the function of the system is realized through sub-microscopic

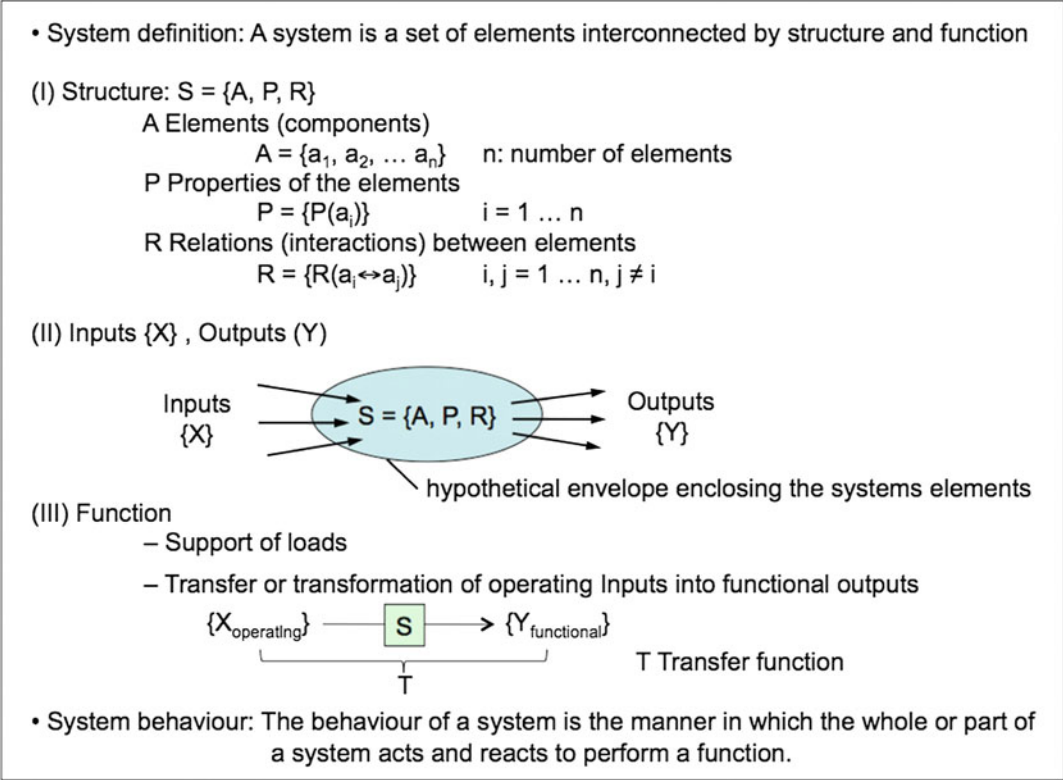


Fig. 2.6 The system concept

System characteristics	Mechanical 2-body system: gear pair	Electrical 2-body system: transformer
System pictogram		
Structure A Elements	a_1 driving wheel a_2 driven wheel	a_1 primary coil a_2 secondary coil
P Properties $P(a_1), P(a_2)$	gear type (e. g. spur, helical, hypoid) pitch diameters, modules, etc	coil type (e. g. single, bifilar) number of turns, etc.
R Relations $R(a_1 / a_2)$	Hertzian tribo-contact mechanics traction, friction, pitting, etc.	inductive coupling eddy current effects, etc.
Function X Inputs	input speed n_x input torque τ_x	input voltage u_x input current i_x
Y Outputs	output speed n_y output torque τ_y	output voltage u_y output current i_y
T Transfer function	$T: (n_x, \tau_x) \longrightarrow (n_y, \tau_y)$	$T: (u_x, i_x) \longrightarrow (u_y, i_y)$

Fig. 2.7 Application of the systems description to simple technical systems

electronic processes (possibly influenced by electromigration, see Sect. 3.3), but the (macroscopic) structure of the system remains constant with time. If this condition is met, the transfer function (T) can be worked out mathematically. This has led to various applications of the powerful “electrical systems network theory”. For condition monitoring of these systems, the control of the functional input–output relations may be sufficient.

- In the mechanical system, however, the structure of the system may change with time due to the interfacial Hertzian tribo-contact mechanics of the interacting gears. The tribological processes may cause wear damage of the gear pair (“pitting”) and these internal structural changes lead to externally measurable vibrations and wear debris. This disturbs the transfer function (T). Therefore, both the systems inputs {X} and outputs {Y} as well as the systems structure {S} and its changes have to be monitored.

2.3 Systems Approach to Technical Diagnostics

The systems concept illustrated in Fig. 2.6 implies that for technical diagnostics of structures, systems, and components, both “Structural Integrity Assessment” and “Functional Performance Assessment” have to be performed. This is shown schematically in Fig. 2.8 in an overview diagram using the abstract systems theory symbols.

Consider as an example of systems thinking in technical diagnostics a rotary machine equipment [7]. As exemplified in Fig. 2.9 the technical system, characterized by its structure and function (to be specified for the actual machine type under consideration), may have faults, for example cracks in critical components. The associated fault symptoms can be examined by vibration analysis (measurements of magnitude/frequency ranges of displacement, velocity, acceleration of stationary and moving machine parts). A diagnosis may be made after root cause analysis and data processing [8]. If the causes of faults or failures can be related to the systems characteristics, structural integrity assessment and functional performance assessment can be made.

Performance parameters for technical systems are exemplified in Fig. 2.10 [9].

Changes of performance parameters observed in condition monitoring can indicate symptoms of fault occurrence. This is illustrated in Fig. 2.11 for the example of technical diagnostics of a reciprocating internal combustion engine [10].

The compilation of Fig. 2.10 shows that (external) functional parameter changes, like temperature, pressure, fuel flow, can be symptoms of fault occurrence in the (internal) systems’ structure, namely detrimental changes of the components of the system and their interactions. Combining systems thinking with the concepts, methods and techniques outlined in the first chapter, a general scheme for the application of technical diagnostics results, which is shown in Fig. 2.12.

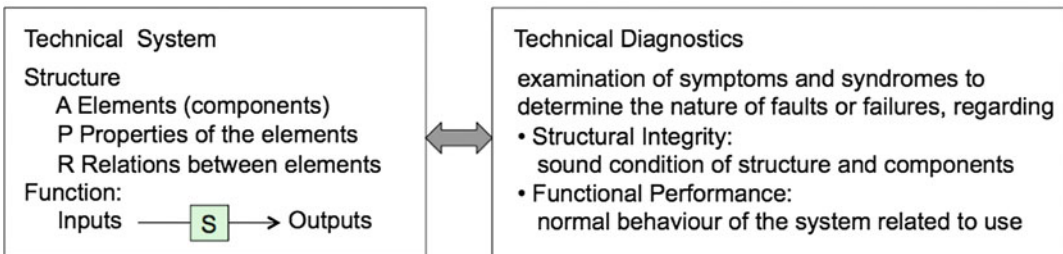


Fig. 2.8 Systems approach to technical diagnostics application

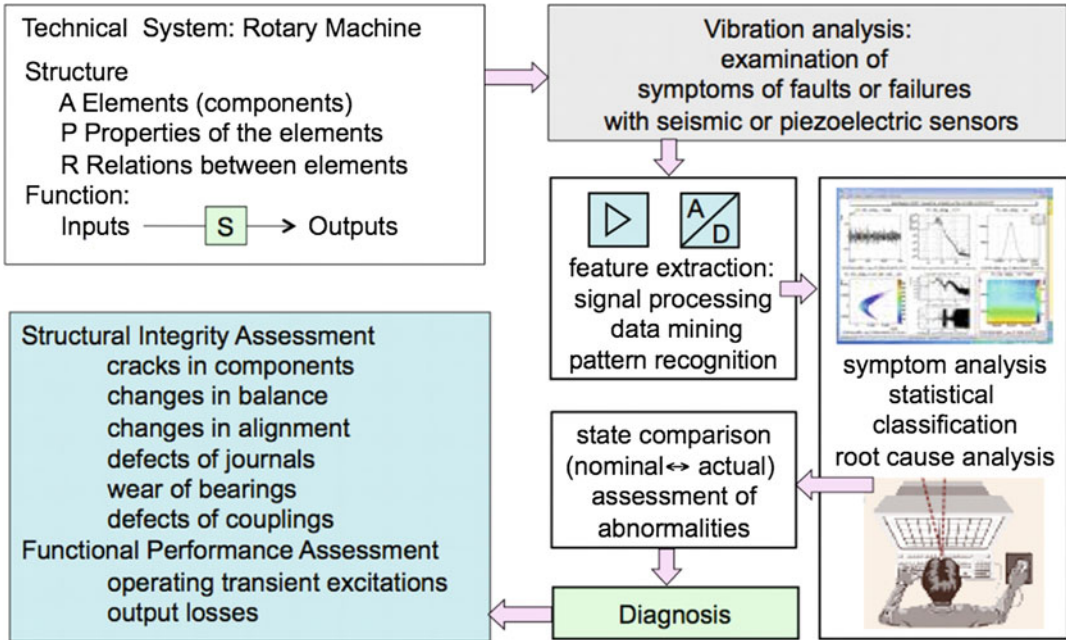


Fig. 2.9 Application of systems thinking in the technical diagnostics of a machine

Parameter	Technical system (machine type)						
	Electric motor	Gas turbine	Pump	Compressor	Electric generator	Fan	Internal combustion engine
Temperature	★	★	★	★	★	★	★
Torque	★	★		★	★		★
Pressure		★	★	★		★	★
Speed	★	★	★	★	★	★	★
Vibration	★	★	★	★	★	★	★
Voltage	★				★		
Current	★				★		
Air flow		★		★		★	★
Fluid flow			★	★			
Fuel flow		★					★
Oil pressure		★	★	★		★	★
Input power	★		★	★	★	★	
Output power	★	★			★		★
★ indicates condition monitoring measurement parameter is applicable							

Fig. 2.10 Examples of condition monitoring parameters for different technical systems

Fault	Performance parameter change						
	Engine temperature	Cylinder pressure	Fuel flow	Vibration	Output power	Oil consumption	Oil debris
Air inlet blockage	★	★					
Fuel injector fault	★	★	★	★	★	★	
Ignition fault	★	★	★	★	★	★	
Cooling module fault			★			★	★
Seal leakage						★	
Piston ring fault		★			★	★	★
Gear defects				★			★
Bearing wear				★			★

★ indicates symptoms of fault occurrence in the systems structure

Fig. 2.11 Examples of performance parameter changes indicating symptoms of fault occurrence

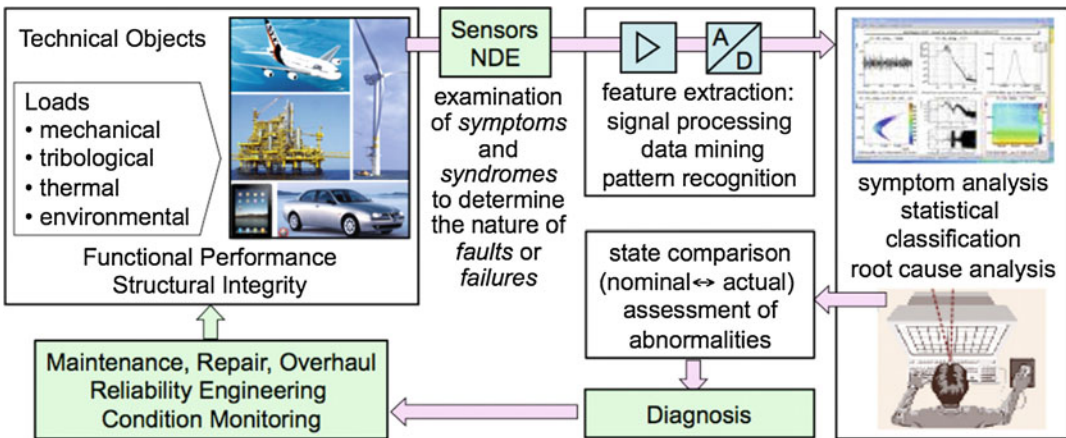


Fig. 2.12 A general scheme for the application of technical diagnostics

The methods and techniques for diagnostics and monitoring are described in detail in Part B of the Handbook. Technical diagnostics of machines

and plants is treated in Part C and structural health monitoring is presented in Part D of the Handbook.

Handbook part	Topic	Chapter no
B Methods and techniques for diagnostics and monitoring	Overview of diagnostics and monitoring methods and techniques	4
	Stress and strain determination	5
	Modal analysis	6
	Vibration analysis	7
	Acoustic emission	8
	Nondestructive evaluation	9
	Infrared thermography	10
	Industrial radiology	11
	Computed tomography	12
	Embedded sensors	13
	Micro-diagnostics	14
	Surface chemical analysis	15
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C Technical diagnostics of machines and plants	Principles and concepts of technical failure analysis	17
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