# MACHINE ELEMENTS – COORDINATION WITH DESIGN SCIENCE

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*Keywords: Machine element, function structure, organ structure, constructional part*

## 1. Introduction

This paper is a continuation of a paper delivered in 2004 [Eder 2004]. Machine elements has long been a staple subject for mechanical engineering education, and an extensive literature exists, e.g. [Doughtie 1964, Faires 1965, Spotts 1985, Juvinall 2000]. Nevertheless, there is a general lack of a systematic classification, the literature presents partly-ordered listings, examples of existing machine elements, and extensive engineering science analysis, with little attempt at revealing the underlying principles. Such a classification would be useful in the context of design engineering. For teaching engineering, it provides an 'advanced organizer' for the information about machine elements [Bruner 1960 and 1966], as a pedagogic aid to help students build that information into their own mental schemata [Eder 2005a and 2005b]. It also provides a basis for applying machine elements to solve problems of design engineering.
Technical Systems are tangible products of an enterprise that have a substantial engineering content. They are intended to be used, as operators of a transformation process, see figure 1, working together with the other operators.

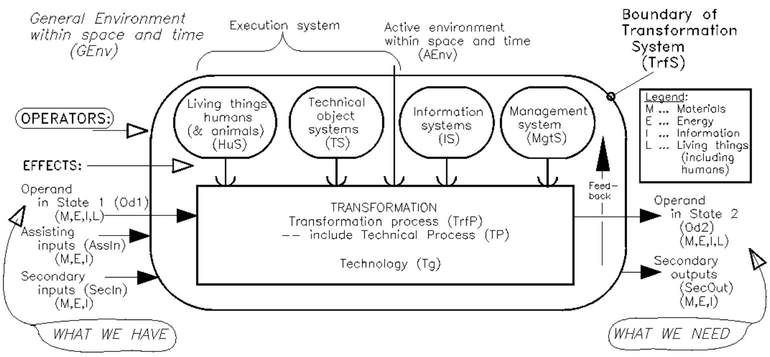



*Figure 1 General Model of a Transformation System*

Figure 1 shows a generalized model of a transformation system (TrfS), with its processes (TrfP) and their technologies (Tg), its operators: human systems (HuS), technical systems (TS), information systems (IS), management systems (MgtS), and environment systems (EnvS). Inputs to the transformation system include the operands that are to be transformed in the process from their initial state (Od1), assisting inputs (to the process, and to the operators), and secondary inputs (mostly disturbances). Outputs from the transformation system include the operands in their ending state (Od2), achieving this state Od2 of the operands (obtaining the change of properties of operands) is the intended *purpose* of the

transformation. Outputs of the TrfS also include the secondary outputs (including those from the operators), some of which can be beneficial, some can be re-used for other purposes, and some are disturbances, pollutants, and other negative influences on the active (and general) environment. Feedback usually exists from outputs (measurements, comparisons with desired outcomes) to inputs to adjust the outputs closer to the desired states.
For our purposes, the TS is the operator of interest. The TS needs to be capable of performing a given task, a purpose function [Hubka 2001], and therefore needs its specific TS-internal functions. The TS should have been designed and manufactured to be suitable for this purpose, it should be in a state of 'operating' or 'being operated' (e.g. by a human), and the operand must be present. It must usually be designed so that it can perform its duties, to deliver the necessary effects to transform the operand, the TS-trans-boundary functions. Four degrees of complexity of TS have been defined [Hubka 1996], compare figure 2:

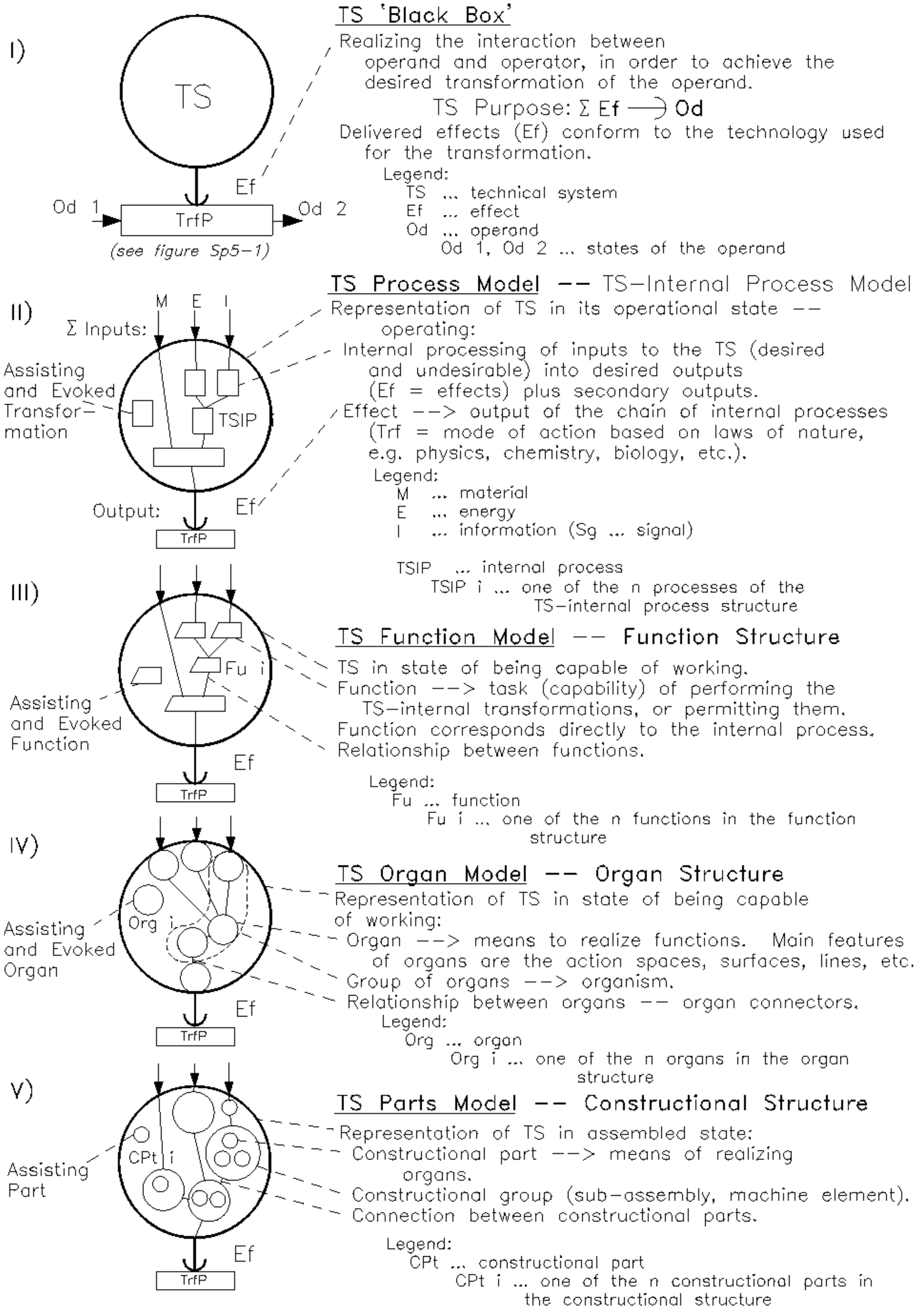
*Complexity level IV – plant*;
*Complexity level III – self-contained functioning system* (machine);
*Complexity level II – sub-system* (sub-assembly, module);
*Complexity level I – constructional part*.

| Level of Complexity | Technical System | Characteristic | Examples |
|---|---|---|---|
| I (simplest) | Constructional part | Elemental system, usually produced without assembly operations -- appears in parts list | Bolt, shaft, bearing sleeve, spring, washer |
| II | Group, mechanism, sub-assembly | Simple system consisting of constructional parts that can fulfill some higher functions | Gear box, hydraulic drive, spindle head, brake unit, clutch, shaft coupling |
| III | Machine, apparatus, device, equipment | System that consists of sub-assemblies and constructional elements (components) that together perform a closed function | Lathe, motor vehicle, electric motor, crane, kitchen machine |
| IV | Plant, equipment, complex machine unit | Complicated system that fulfills a number of functions, that consists of machines, sub-assemblies, groups and constructional parts, and that constitute a spatial and functional unity | Hardening plant, machine transfer line, factory equipment, refinery, underground transportation system |

*Figure 2 Levels of Complexity of Technical Systems*

## 2. Structures and their Significance

Several structures of technical systems have been identified in Engineering Design Science [Hubka 1996], as useful for design engineering, especially in conceptualizing novel or innovative systems. The most important of these structures are: the function structure, the organ structure, and the constructional structure. Every technical system carries all of these structures, whether they have been deliberately designed or not. The structures can easily be recognized by a knowledgeable person. Each such structure is composed of elements (functions, organs or constructional parts respectively) and their relationships within the system and across its boundaries, see figure 3.
Each structure can consist of various kinds of the appropriate elements, typically as shown in figures 4 and 5 for functions and organs respectively. The typical structures for constructional parts may be found in the usual layout, detail and assembly drawings (or their computer-resident representations), they are so well known that no further definition is needed. The detail drawings show the *elemental design properties*, see figure 6, of form, material, kind of manufacturing, dimension, tolerance, surface condition, etc. Assembly drawings show the structures, and reveal the *design characteristics* such as action sites, mode of action, mode of adjustment, etc. The *general design properties* are shown in the design report that records




Literature:
Hubka, V. (1984) Theorie technischer Systeme, Berlin: Springer-Verlag, Abb. 5.4
Hubka, V. & Eder, W.E. (1988a) Theory of Technical Systems, New York: Springer-Verlag, Fig. 5.4

*Figure 3 Structures of Technical Systems – Part A: Principles*

Example: machine vice in operational state -- state of capability of working.

ABSTRACT MODEL

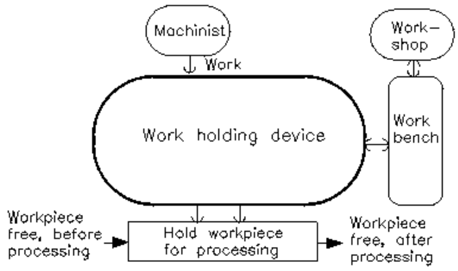
CONCRETE MODEL

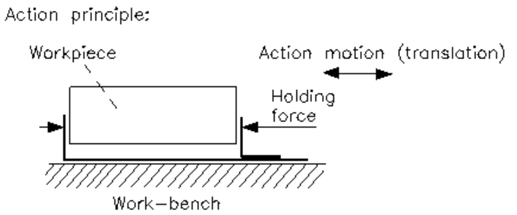
I) BLACK BOX

Design specification, Requirements specification -- from customer, or potential user

Contract specification -- company level

Designers' working specification -- designers' approved interpretation

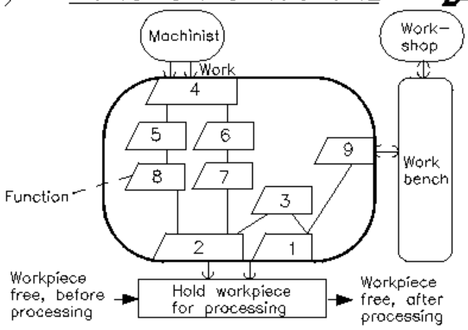



II) PROCESS STRUCTURE

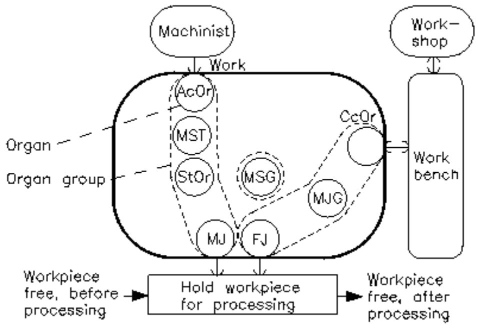
not illustrated -- elements of the function structure and the TS–internal process structure are in one–to–one correspondence, each function implements the capability to perform the corresponding TS–internal process.

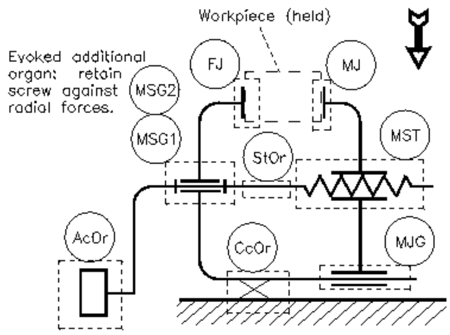
III) FUNCTION STRUCTURE



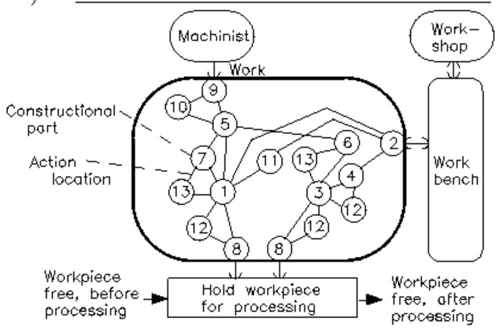

| | FUNCTIONS (Fu) | ORGANS (Org) | |
|---|---|---|---|
| 1 | FORM fixed holding surface<br>TRANSMIT holding action | Fixed jaw | FJ |
| 2 | FORM movable holding surface<br>TRANSMIT holding action | Movable jaw | MJ |
| 3 | GUIDE movable holding surface rel. to fixed holding surface | Guidance for movable jaw | MJG |
| 4 | FORM the action surface<br>ACCEPT work | Acceptance organ | AcOr |
| 5 | TRANSFORM rotation to translation | Motion screw thread organ | MST |
| 6 | AMPLIFY force | | |
| 7 | STORE energy for holding (strain energy) | Storage organ | StOr |
| 8 | RETAIN position against holding force | Motion screw guidance organ | MSG |
| 9 | FORM contact to fixed system<br>PERMIT making connection | Connection organ | CcOr |
| 10 | REACT axial force | Motion screw guidance organ | MSG1 |
| 11 | Evoked: REACT radial force from work acceptance | Motion screw guidance organ | MSG2 |

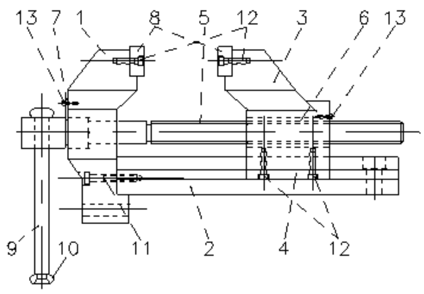
IV) ORGAN STRUCTURE




V) CONSTRUCTIONAL STRUCTURE (COMPONENT or ANATOMIC STRUCTURE)



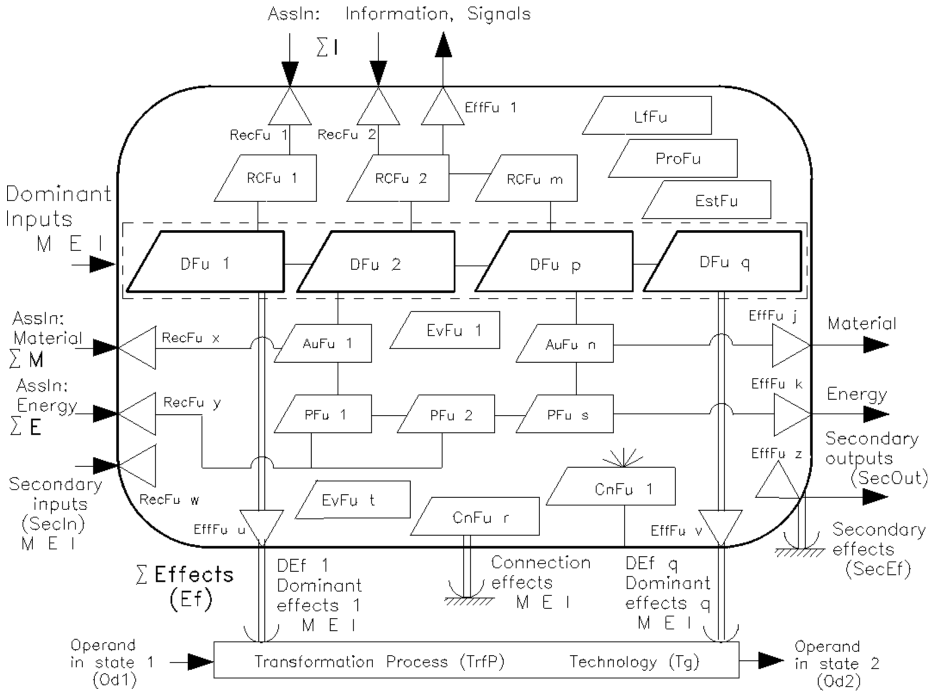




Parts List: (CPt)

1 Fixed jaw
2 Base
3 Movable jaw
4 Guide plate
5 Motion screw spindle
6 Nut insert
7 Keeper plate
8 Jaw plate (hardened)
9 Handle
10 Handle knob
11 Screw
12 Screw
13 Screw

Detail drawings (and/or computer files)
Parts lists
Purchased components lists
etc.

*Figure 3 Structures of Technical Systems – Part B: Examples* the estimations, calculations and simulations used to predict the behavior of the future TS. The external properties are generated by designing the internal properties. Knowing these kinds of elements and their properties, engineering designers can use them as check-lists to verify that their considerations are as complete as possible at that stage of designing.




PuFu ... Purpose functions (active and passive) describe the combined dominant effects, the main technical process (transforming the operands) and the technology to transform the operand
DEf ... Dominant effects needed to implement, drive, operate the technical processes
DFu ... Dominant functions (active and passive) needed to generate the dominant effects
AssFu ... Assisting functions (active and passive) needed to directly support the dominant functions, including:
  AuFu ... Auxiliary functions (materials converting and delivering)
  PFu ... Propelling functions (energy converting and delivering)
  RCFu ... Regulating and controlling functions (information converting and delivering)
  CnFu ... Supporting and connecting functions, TS–internal and to external systems (fixed or environment systems)
TrBFu ... Trans–boundary functions:
  EffFu ... Effector functions
  RecFu ... Receptor functions
EvFu ... Evoked functions, needs for properties recognized during designing
  ProFu ... Production functions needed to enable manufacturing, assembling, testing, adjusting, servicing, commissioning, etc.
  LfFu ... Life functions needed to support cleaning, storing, transporting, safety, reliability, maintainability, etc. of the technical system
  EstFu ... Esteem and other functions to enhance human, social, economic and legal acceptance.

*Figure 4 Model of the Function Structure of Technical Systems*

The different structures are, of course, related:

(1) TS-internal functions are recognized from the effects that the TS is intended to exert on the operand of the transformation process, and describe the TS-internal and cross-boundary action capabilities of a TS [Hubka 2001]. ;

(2) organs (and their structure) realize the needed functions (and their structure), they generally are connections between action locations, where constructional parts act on one another by means of a mode of action; and

(3) organs are embodied in the constructional parts (and their structure).

This sequence of structures can be significant for design engineering, see section 4 of this paper.

The relationship between organs and constructional parts is complicated. Some sections of the boundary of a physical constructional part will constitute a part of the action locality contained in a particular organ (e.g. the bearing diameter and shoulder of a shaft). The mating action locality that completes the organ will exist on another constructional part. The form of that action locality depends on the function needed at the organ. Others sections of the constructional part will not be restrained by TS-functions, e.g. manufactured surfaces of constructional parts that are only in contact with a non-functional environment (e.g. air), the forms of these sections may be chosen according to other criteria.

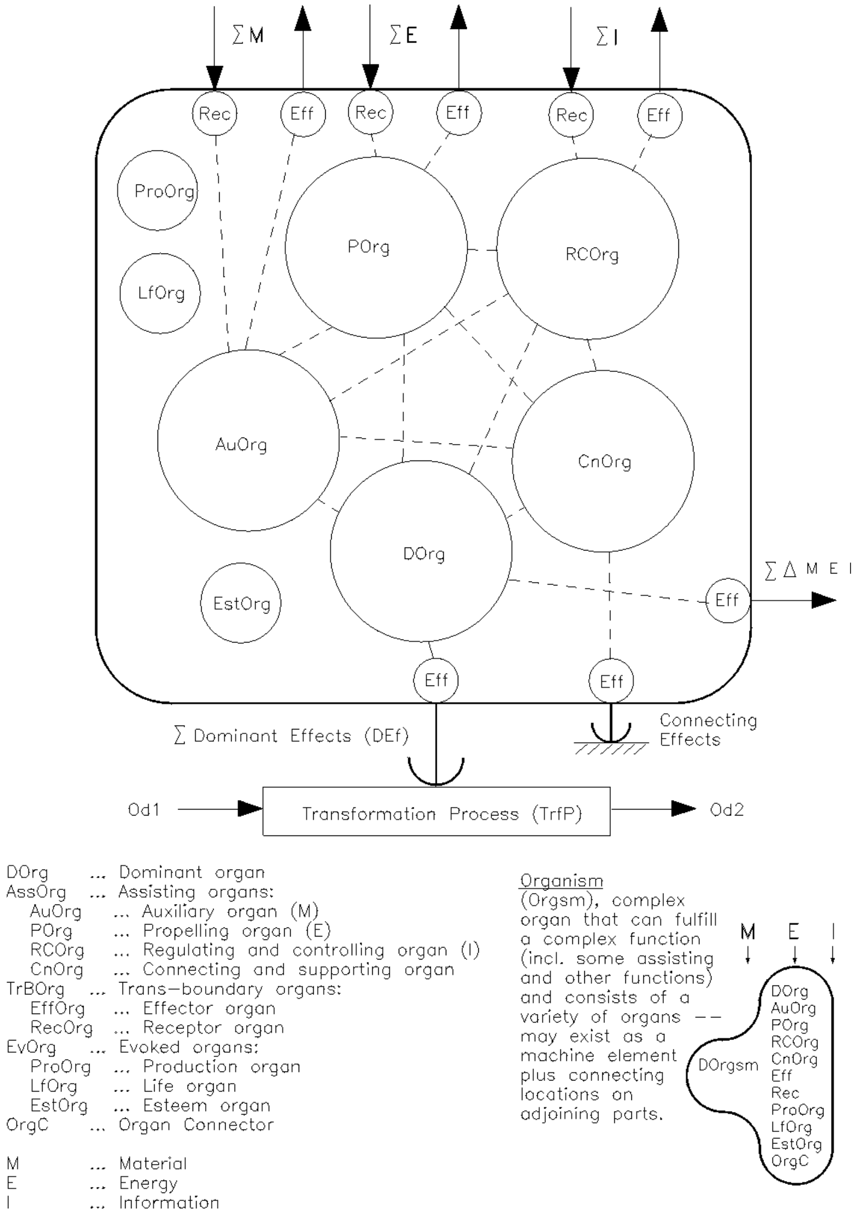



*Figure 5   Model of the Organ Structure of Technical Systems*

The relationship between organ structures and constructional structures is also complicated. Referring to the representation shown in figure 3, part 2, left column, if both diagrams of structures are complete, the nodes in the organ structure represent individual organs, and the arcs represent connecting organs. The organs are embodied by arcs in the constructional structure, and the connecting organs are embodied in the constructional parts which are represented as the nodes in the constructional structure.

For design engineering, and consequently for education, a good formulation of the elements is useful. Functions should be defined in words as a combination of a verb (or verb phrase) and a noun (or noun phrase) that describe what change to which property takes place (or is intended). Organs are selected to perform a function, and should be defined in words and/or diagrams that show which (intended) constructional part interacts with which other part. Constructional parts are designed to carry and connect organs, and should be defined in words, symbols (including numbers), graphical representations, etc. that show the elemental design properties of form, dimension, material, type of manufacturing, tolerance, surface quality, etc., see figure 6

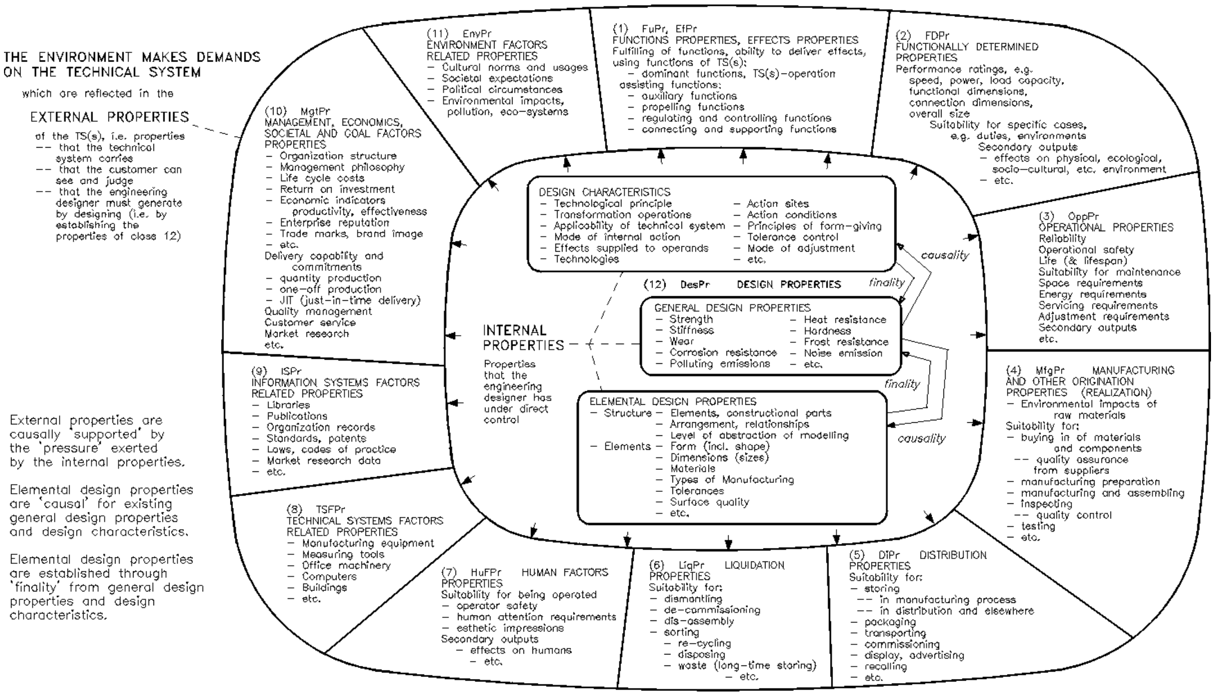



*Figure 6 Classes of Properties of Technical Systems*

## 3. Classification of Machine Elements

Machine elements are conventionally defined as technical systems of lower complexity (levels I and II) that are frequently used as known and proven solutions for functions in technical systems. They are mostly regarded as mechanical engineering items [Doughtie 1964, Faires 1965, Spotts 1985, Juvinall 2000].

Sub-dividing machine elements according to their complexity leads to one form of categorization.

One category of simple machine elements consists of *elemental organs*. Many of these elemental organs constitute ‘machine elements’ in the conventional literature, e.g. press fits, splines and serrations, sliding bearings, friction faces, etc. Each such elemental organ usually consists of a pairing of the action locations existing on two interacting constructional parts.

The second category of simple machine elements provides connections among the action locations on an individual constructional part, fulfills the connecting and supporting functions, provides the connecting and supporting organs to the elemental organs, and embodies the connecting organs and functions, e.g. shafts, gaskets, springs, belts and chains (the sections between contact points), etc. Such machine elements appear as individual constructional parts – complexity level I. Their general design properties are probably the most significant.

All other machine elements are *organisms*, composed of several elemental organs and their connections. They exist as assembly groups, modules, sub-assemblies or mechanisms (e.g. rolling contact bearings, couplings, brakes, power transmission units) – complexity level II. Each of these organisms has its cross-boundary action locations (as partial organs) which interact with the adjoining constructional parts. Organisms may be regarded as ‘black boxes’ for the purpose of conceptualizing an organ structure for a TS. They need only be resolved

into elemental functions, organs and constructional parts for the purpose of designing the machine element.
In the conventional literature, such mechanical principles as (static or dynamic) hydraulic, thermal or control elements usually do not appear [Albers 1999]. Nevertheless, similarly recurring parts exist in other engineering disciplines, e.g. steel-reinforced concrete columns (civil engineering), distillation columns (chemical engineering), diodes (electronic engineering), etc. A wider definition to include these parts is needed, e.g. as *engineering design elements* [Weber 1997].
The dominating TS-internal processes are described as the capabilities of the TS, its TS-internal functions. These dominating TS-internal processes concern energy. Materials and information need energy for their processing. Each type of energy is characterized by (a) a static, ‘across’, tension property – a ‘state variable’, and (b) a dynamic, ‘through’, rate property – a ‘flow variable’, see figure 7. Power is the vector product of a state variable with a flow variable.

| Forms of Energy | Typical Physical Quantities | | | |
|---|---|---|---|---|
| | State Variable (static, ‘across’ variable) | Flow Variable (dynamic, ‘through’ variable) | Power ( = state x flow variables) $P = dW/dt$ | Work $W = \int P.dt$ |
| Mechanical translational | force $F$ | velocity $v = ds/dt$ | $P = F.ds/dt = F.v$ | $W = \int F.v.dt = \int F.ds$ |
| Mechanical rotational | torque $M = F.r$ | angular velocity $\omega = d\alpha/dt$ | $P = M.\omega = F.d\alpha/dt$ | $W = \int M.\omega.dt = \int M.d\alpha$ |
| Fluid | pressure $p = F/A$ | volume flow rate $\dot{V} = dV/dt$ | $P = \triangle p.dV/dt$ | $W = \int \triangle p.dV$ |
| | | mass flow rate $\dot{m} = dm/dt$ | $P = \triangle p.\dot{m}/\rho$ | $W = \int \triangle p.m.dt/\rho = \int \triangle p.dm/\rho$ |
| Electrical | voltage $U$ | electric current $I = dQ/dt$ | $P = U.I = U.dQ/dt$ | $W = \int U.I.dt = \int U.dQ$ |
| Thermal | temperature $T$ | entropy $\dot{S} = dS/dt$ | $P = \triangle T.\dot{S} = \triangle T.dS/dt$ | $W = \int \triangle T.S.dt = \int \triangle T.ds$ |

*Figure 7 Types of Energy*

Machine elements, redefined as *design elements* [Weber 1997], are carriers of a (simple or more complex) function. The typical generic verbs of their function (i.e. as flows) are applied to non-specific energy (as noun) to formulate the TS-functions for an organ and/or design element. These verbs include mainly (1) transmit, (2) reduce/increase, (3) connect/disconnect, (4) store, (5) divide/unite, (6) transform, (7) distribute/combine, (8) distribute/collect, (9) separate/mix, and many others.
Engineering Design Science [Hubka 1996] recognizes four transformation processes: (A) processing to change *structure*, (B) manufacturing to change *form*, (C) transporting to change *location*, and (D) storing to change the *time* coordinate; and these can be applied to four kinds of operands: (a) materials, (b) energy, (c) information/signals, and (d) humans and other living things, giving 16 ‘pure’ transformations – and many more combinations.
The verbs of function can be characterized in this sense as: (5) ‘divide/unite’ is a transformation of *structure*; (6) ‘transform’ is a transformation of *form*; (2) ‘reduce/increase’ is a special case of ‘transform’, from one form to the same form; (1) ‘transmit’ is a transformation in *location*, and is often a special case of ‘reduce/increase’; (3) ‘connect/disconnect’ is a special case of ‘transmit’; (4) ‘store’ is a transformation in *time*; (2) ‘reduce/increase’ can also be accomplished by serial application of two successive ‘transform’ (6) operations, e.g. mechanical rotation to hydrodynamic flow to mechanical rotation, as in fluid couplings and torque converters. A systematic classification of design elements (in general) according to function verbs [Weber 1997, Eder 2004] is shown in figures 8 and 9. Note that these tables include many elements that are obviously not simply mechanical.

| Forms of Energy | 'Function' Verbs — Verbs of TP operand transformation, or of TS–internal function | | | |
|---|---|---|---|---|
| | transmit | reduce/increase | connect/ disconnect | store |
| Mechanical translational | rods, links, cables, belts, chains, connection elements (e.g. connecting rod), guidances, ... | levers, wedges, pistons, ... | ratchet mechanisms, traction couplings, mechanical flip–flops, ... (connect) welding, soldering, adhesive bonding, riveting, ... | springs ('static' strain energy), counter–weights ('static' potential energy), inertia masses ('dynamic' kinetic energy), ... |
| Mechanical rotational | shafts, keys, splines, serrations, cotters, clamp connections, force and shrink fits, couplings, bearings (sliding, rolling), guides, ... | gears, belts, timing belts, chains, friction drives, flat and vee belts, ... | clutches, brakes, ... | torsion springs ('static'), flywheels ('dynamic'), ... |
| Hydrostatic Pneumatic | pipes, tubes, fittings, ... | | valves, ... | pressure vessels, hydraulic accum–ulators, ... |
| Hydrodynamic Aerodynamic | vanes, guides, wings, ... | diffusers, ... | valves, ... | |
| Electrical | wires, fuses, ... | transformers | insulation, switches, ... | capacitors ('static'), accumulators, inductors ('dynamic'), ... |
| Electronic (analog, digital) | conductors, ... | amplifiers, attenuators, chokes, inductors, ... | transistors, diodes, ... | magnetic memory, ... |
| Thermostatic | heat pipes, cooling fins, ... | heat exchangers, boilers, condensers, ... | thermal insulation, fractionators ... | heat storage units (fire–brick), reactor vessels |
| Thermodynamic | combustors, spray nozzles, ... | heat pumps, ... | diverter channels, ... | |
| NOTE: | special case of 'reduce/increase' if value and form of output = input | special case of 'transform' (see figure Sp7–12) if form of output = input | addition to 'transmit' | |

*NOTE: Functions should normally be formulated as a combination of a verb (or verb phrase) and a noun (or noun phrase). Both the verb and the noun should be chosen appropriate to the specific TP and TS–'sort'.*

Literature:
Weber, C. and Vajna, S. (1997) 'A New Approach to Design Elements (Machine Elements)', in WDK25 -- Proc. ICED 97 Tampere, Tampere University of Technology, p. 685–690

*Figure 8 Classification of Engineering Design Elements for Various Verbs*

These functions, and the functions by which the operational TS reacts to the operand and the operational situation, are the indicators for analytical methods from the engineering sciences that can help in evaluating a proposed TS, and for establishing the needed sizes (and sometimes forms) of constructional parts. A first approach will usually be a 'quick and dirty' estimate, followed by a better estimate based on a 'static' view, e.g. maximum stress from static loading. If needed, a 'dynamic' investigation and simulation can follow, e.g. vibration behavior, for which a four-pole simulation model can be employed [Weber 2005a and 2005b].

More extensive classifications may become too complex for human searching (compare design catalogs [Roth 1995, Koller 1985, Ehrlenspiel 1995]), and may be better implemented in computer-resident form, e.g. using hypermedia [Birkhofer 1997]. Such a structure of information, adapted to mechanical couplings, may show many dimensions, see figure 10.

| Forms of Energy / Transform to: / Transform from: | Mechanical translational | Mechanical rotational | Hydrostatic Pneumatic | Hydrodynamic Aerodynamic | Electrical | Electronic | Thermostatic | Thermodynamic |
|---|---|---|---|---|---|---|---|---|
| Mechanical translational | (see 'reduce/ increase') | wheels, rack and pinion, slider-crank, motion screws | cylinder/ piston | | linear generators | linear transducers piezo, lvdt, strain gage | linear brakes | reciprocating gas compressors |
| Mechanical rotational | wheels, rack and pinion, slider-crank, motion screws, cams | (see 'reduce/ increase') | hydrostatic pumps | turbo-pumps | rotary generators | rotary transducers | rotary brakes | rotary gas compressors |
| Hydrostatic Pneumatic | cylinder/ piston | hydrostatic motors | (see 'reduce/ increase') | | | pressure sensors, specific gravity sensors | | |
| Hydrodynamic Aerodynamic | water jet | turbines | pitot-static tubes, fluidic control units | (see 'reduce/ increase') | magneto-hydro-dynamic generator | | throttles | |
| Electrical | linear motor, actuator, solenoid | rotary motor, rotary actuator | magneto-hydro-dynamic pumps | | (see 'reduce/ increase') | | electrical resistances | |
| Electronic | mechatronics | mechatronics | | | | (see 'reduce/ increase') | | |
| Thermostatic | linear heat engines, combustion engines | rotary heat engines, combustion engines | | | | heat sensors, temperature sensors | (see 'reduce/ increase') | |
| Thermodynamic | turbojet engines, turboprop engines, ramjets | gas turbine engines | | | | | | (see 'reduce/ increase') |

*Figure 9   Classification of Engineering Design Elements for the Verb 'Transform'*

Energy transfer (in such couplings, and elsewhere) mainly takes place by different manifestations of closure as shown in figure 11, and these form an *information unit* in the hypermedia classification system. Consequently, various existing couplings can be classified in a matrix as shown in figure 12. A search for existing coupling principles according to various criteria is thus possible. This procedure shows some similarity to the morphological matrix.

## 4. Design Methodology

The elements of the transformation system can be used in design engineering. Process operations, technologies, TS-functions and TS-organs can be used for *conceptualizing*. The hardware constructional parts in configuration and parametrization are used for *embodiment* (in sketch layouts and dimensional layouts) and *detailing* (in detail and assembly drawings,

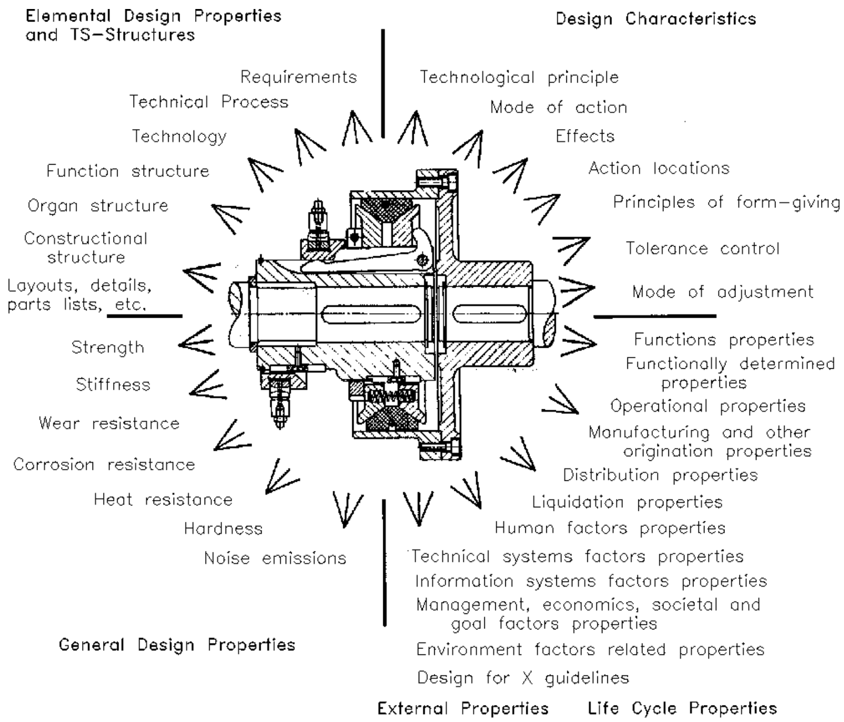



*Figure 10 Machine Elements and Related Information*

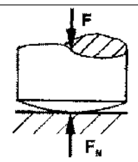
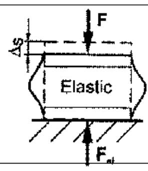
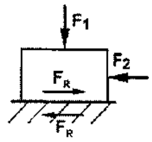
| | Type of Closure Principle | | |
|---|---|---|---|
| | Form Closure | | Friction or Force Closure R |
| | Rigid Contacts F | Flexible Contact E | |
| Iconic Representation |  |  |  |
| Equation | $F_N = F$ | $F_{el} = c \cdot \Delta_S$ | $F_R = \mu_H \cdot F_2$ |
| Types of Stress on Materials and Surfaces | Surface pressure, Hertz contact stresses, Sub-surface shear stresses | Surface pressure Elastic/plastic deformation | Surface pressure, Surface shear stresses, Static friction (limited), Wear |
| Properties and Design Characteristics | With clearance: shock, plastic defor-mation Without clearance: pre-load stresses, high precision of force trans-mission | Relative motion, Rebound (elastic strain energy), Vibrations, Damping, Compensates peaks of force appli-cation | Limited force trans-mission parallel to contact surface, Micro-movement at edge of contact (danger of fretting) Sliding when force exceeds static limit |

*Figure 11 Closure Principles as Classification Criteria for Machine Elements*

parts lists, etc. or their computer-resident equivalent models). Even though all these elements and structures are always present, they need not be used for a particular design engineering problem. The design processes can thus range from ‘purely’ intuitive to very systematic, and can apply several methods (including computer applications) for steps of the design process. During this procedure, one or more computational and/or physical prototypes may be built and tested to verify parts or the whole of the designed technical system.

The transformation process as defined in Design Science [Hubka 1996], figure 1, can be used as a basis for designing, i.e. to define a suitable comprehensive design methodology:

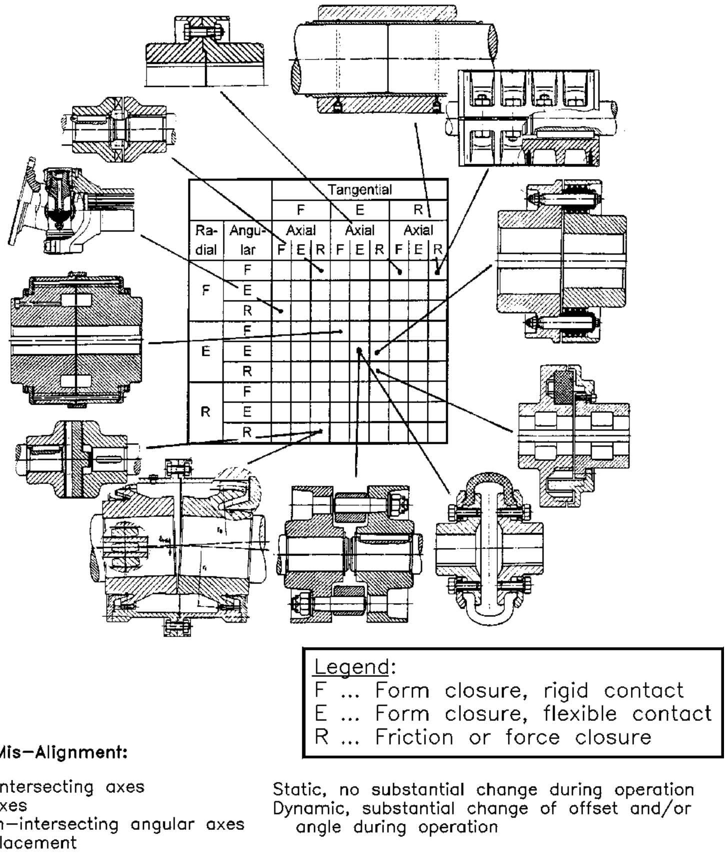



*Figure 12 Classification of Couplings according to Closure Principle*

a) As soon as a designer has understood the transformation process (as a black box, as an object and its theory), figure 1, he/she can apply the appropriate method [Eder 2005c]. This consists of a chain of (intermediate) *goals* for which *means of solving* are to be found, where each means turns into the goal for the next step:

- determine the essential tasks of the transformation process,
- choose a favorable technology,
- establish all necessary output effects of the operators (input effects to the operands needed for transforming them),
- and distribute these optimally among the humans and the technical system in the existing situation, i.e. establish the *technical process*.

This method is preferably used in the phase *clarification of the design task*, although it really already belongs into the solution process (*conceptualizing* phases). It should be obvious that this procedure cannot be completed in such a linear fashion, iterative working is essential, feedback from later stages to earlier ones will progressively drive the solution proposals towards an optimal state, as more is learned about the problem and its possible solutions. If any opportunistic and intuitive step is taken outside this procedure, at least a check should be made to ensure that the results do not violate the procedural considerations and outcomes.

b) The origination and life of the technical system (its life cycle) can be presented very clearly with the help of several models of the *transformation system,* see figure 13. The matrix formed from the life phases and operators of the processes categorizes the areas of *Design for X – DfX* [Hosnedl 1997]. It also presents the search field for properties (including characteristics, attributes) of the technical system to be designed, see figure 6, and these figures are the basis for writing a design specification, as output from the phase *clarification of the design task*.

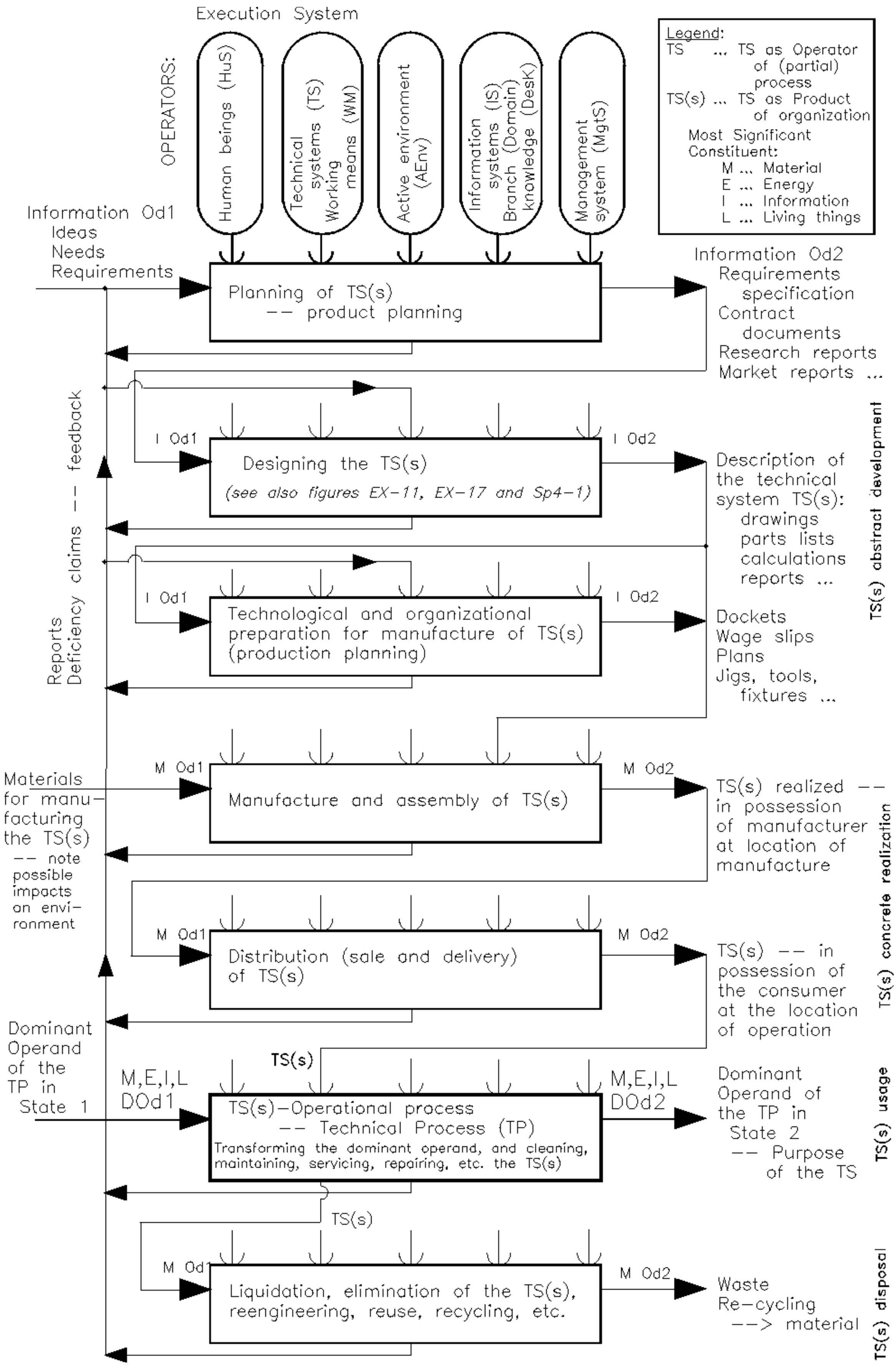



*Figure 13   Life Cycle of Technical Systems*

c) Conceptualizing, embodying, and detailing can be helped by the theoretical models of technical systems, see figure 3. From the method described in a) above, another *goals–means chain* can be traversed:

- the needed (internal and trans-boundary) functions of the system can be established, the *function structure*;
- the organs that are capable of fulfilling the functions can be delineated (e.g. by using a morphological matrix) and combined to establish the *organ structure*; this is the goal of *conceptualizing*, and is the primary point where knowing about available kinds of machine/design elements can help in the design process, especially for the configuration of the future TS. The four-pole simulation model [Weber 2005a and 2005b] can be formulated in principle on the basis of a proposed organ structure, i.e. during the major phase of conceptualizing. At this stage, some conclusions can be drawn about the potential behavior and best arrangement of the constructional parts to assist in developing the constructional structure;
- preliminary layouts can be explored, first part of establishing the *component structure*, in which the design elements can be parametrized in a first-cut 'quick-and-dirty' estimation, as well as a first useful contact with manufacturing – start of concurrent engineering. After this transition to the constructional structure, at the earliest in the preliminary layout, the simulation model [Weber 2005a and 2005b] can be used to verify and investigate the relationships among physical dimensions of constructional parts and their dynamic behavior.
- dimensional layouts generated; this is the goal of *embodying*, and allows a better defined parametrization by more accurate computations, including dynamic simulation if needed [Weber 2005a and 2005b];
- details fully established;
- parts lists generated, detail drawings and check assemblies completed, supply chain investigated; – etc.

This characterizes the steps of progress towards defining the system to be designed. At each step in the chain, several alternative solution proposals can be found, and the most appropriate selected for further processing.

It is also possible (and was demonstrated [Ehrlenspiel 1987]) to search out new principles, and to use systematic variation, especially of active organs and constructional details. According to check lists [Ehrlenspiel 1995, Koller 1985], variations can be: (a) of form, (b) of position or orientation, (c) of number, (d) of size/dimension, (e) of sequence or arrangement, (f) of connecting structure, (g) of connection type, (h) of contact type, (i) of mobility, (j) of constraint, etc. Many patents have been issued on this basis.

Such systematic classification and variation obviously assists (personal, individual and group) creativity, they can produce many hundreds to thousands of possible alternatives. These methods obviously also increase demands for suitable selection and evaluation of alternatives to find those combinations that show technical and economic merit.

It should now be obvious that education for design engineering should include a comprehensive overview of existing machine elements, concentrating on their action locations, their internal mode of action, and their behavior. This information is essential for their application in conceptualizing and laying out of technical systems. A secondary consideration is the design process used to generate a new machine element type or variant, and for this purpose the conventional analysis methods are needed.

## 5. Closure

The subject of machine elements needs urgent revision to reach across the conventional boundaries among engineering disciplines, to include the more recent elemental systems, and to rationalize the process of establishing physical dimensions and verifying the expected behavior of the proposed TS.

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