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Pedagogics of Design Education*

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Pedagogics, a theory and strategy for teaching, is an essential background which can lead to learning. Difficulties of design engineering, and therefore of learning to design in engineering are outlined. Engineering design education aims to bring students to various competencies. The parameters for engineering design education are related to the teaching system. They are outlined with reference to several important questions, which refer to the learners (students) and to the complete teaching situation, including the teachers (and their knowledge and competencies), teaching materials (e.g. books, computers), information on teaching/learning, organization, and environment.

INTRODUCTION

PEDAGOGICS is concerned with the theories of teaching and learning, and should provide a *raison d'être* and guidelines for the practices (the contents, i.e. object knowledge, and the methods, i.e. process knowledge) of teaching that can lead to learning. The overall content for learning for this paper is 'engineering design'. This has been a subject for discussion and investigation for many years within WDK (Workshop Design-Konstruktion)—and informal international organization to investigate the science about engineering design, [e.g. 1–3], and other groups. This work is now continuing under a new organization, The Design Society.

'Learning' is used (a) as a noun, the sum of the acquired (internalized and categorized) knowledge directly accessible to a learner, but also (b) as a verb, the process of acquiring knowledge. Learning (as a noun or as a verb) should be supported by a body of theory and by experience from practice. We will concentrate on the use of this word as a verb, an activity of a learner, a student.

We also distinguish between 'design' as a noun, meaning *products, artifacts, technical systems*, and 'design' as a verb, a process of establishing and synthesizing which of several ways things could (best) be done, and how to implement that choice, *designing*. Again, theory and practice need to be involved.

This confirms the division of knowledge (with some overlap) into two axes: theory and advice for practice, and object-related and process-related knowledge, as proposed in the subject of Design Science [4], see Fig. 1. Object knowledge is usually examinable by relatively objective tests. Procedural (mental process) knowledge tends to be learned in such a way that its use tends to become automatic, sub-conscious, and (when sufficiently well absorbed) the user is no longer aware of its use.

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DESIGNING

Designing is difficult in many respects. The usual first difficulty is starting to design, where and how to begin, overcoming a natural fear of reaching into the unknown. This is compounded by the scope of designing—engineering designers intend to make something that can perform a duty, where the internal mechanism is the important means; industrial designers intend to make something that will appeal to the customer. The two scopes overlap in many respects, and are complementary in many others; but each has its own outlooks, methods and models. Engineering design can work with abstract transformation processes, internal functions (and function structures), organs (and organ structures), constructional parts (and constructional structures), and other significant aspects of the things that make a technical system work; the resulting external form tends to be somewhat secondary. Industrial designers are more concerned about the overall conception and appearance, interactions with humans, product management, and cost/benefit structures, and much less with the internal structures and modeling; they thus tend to work in a real domain that is close to the constructional structures (the structures of tangible, real parts).

Designing needs a variety of knowledge, some of which must be internalized and understood, but much must be retrieved from external sources, interpreted and understood. As shown in Fig. 1, this knowledge includes items derived from science, technology, experience, society, economics, and many others. It includes objective and subjective forms, especially also 'know-how' and heuristic advice (guidelines, convention values,

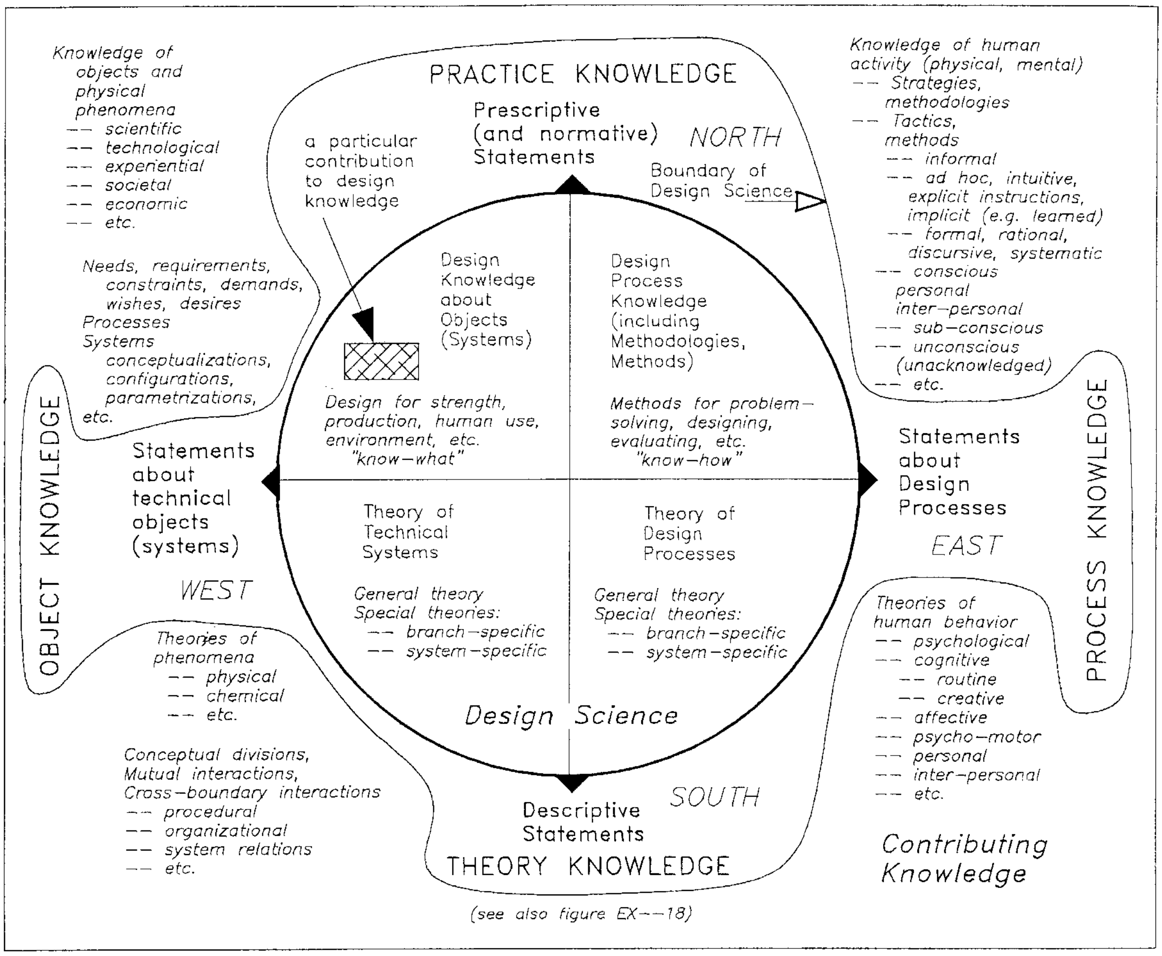


Fig. 1. Model map of Design Science—survey.

successful prior art, etc.). It can be in different forms according to its potential use, as records of knowledge, adapted for teaching and learning, adapted for designing, etc.

Designing is also difficult because it needs a certain appropriate openness of mind, a capability to search for alternative solutions, usually classed as creativity [5, 6].

We can recognize within designing a general division of activities into:

- clarifying the problem,
- conceptualizing,
- embodying, laying out,
- elaborating, detailing.

Design Science [4] recognizes various subdivisions, related to possible structures of technical systems. But designing is not a linear sequence of activities, it involves feedback, iteration, and recursion. Within these activities, problem solving occurs, which can be sub-divided into recognizable activities of:

- defining the problem,
- searching for solutions (includes synthesizing, and resolving technical conflicts in requirements and properties),
- evaluating/deciding (includes analyzing/diagnosing/selecting, prototyping);
- communicating (verbal, graphical, symbolic);
- obtaining and preparing information (includes research);
- verifying/checking;
- representing (verbal, graphical, symbolic).

Designing contains aspects of both artistic behavior and of science 'application', yet designing is neither merely art nor just applied science [7]. Designing of engineering (technical) systems means that many constraints must be considered, such as:

- satisfying customers, fulfilling their needs as well as appealing to their senses;
- providing economic survival and profitability for the enterprise;
- remaining within laws, conforming to standards and ethical considerations;
- etc.

Design problems range from those requiring relatively routine solutions based on generally well-developed knowledge and existing systems, to those demanding highly innovative solutions.

Designing is also a social activity; it affects the structure and operation of society, and it takes place within a social structure of a 'designing and manufacturing team', usually an industry, a company, an enterprise. Designers at times work alone (as employees or as consultants) within a 'discipline', e.g. mechanical, electrical, civil or other engineering, or in a hybrid of these. At other times they must work in a team—which may cover a single 'occupation' (e.g. designing) and/or multiple occupations (manufacturing, selling, buying, packaging, ergonomics/esthetics, etc.). Designing may need human conflict resolution, overcoming 'group think', detecting and avoiding errors, etc.

Education for engineering design, of engineering designers, should take most of these considerations into account—it is consequently more difficult than education for the analytical engineering sciences. The engineering sciences are necessary for designing, but not sufficient. The basic phenomena must be understood by developing a 'feel' for them, but so must the human, social, economic and other fields. This understanding allows designers faced with a problem to look for candidate solutions that use various principles (from an engineering discipline or experience, e.g. electrical, mechanical, hydraulic) to achieve the required effects.

There are many opportunities for designers, if their capabilities are suitable. Education can attempt to match the needs of industry that designers should be immediately capable of being productive in designing. But this is not possible; all designers need time to become sufficiently familiar with the product family (a TS-'sort') and the procedures of their employing industry branch or sector. In the recent past, this time has extended to about ten years.

PROBLEMS OF ENGINEERING DESIGN EDUCATION

In view of this outline of designing, what can be done to shorten the time for a designer to reach adequate competency in designing? It is generally acknowledged that engineering designers need to be active for about ten years before they can be regarded as fully competent. As defined in [8], sub-groupings of competency cover the following aspects:

- heuristic competency—use of 'rules of thumb', guideline values, intuitive guesses, etc.;
- branch-related competency—knowledge and experience is not always readily transferable from one family of systems to another;
- methods-related competency—synthesis methods, analysis methods, design methods, methods for computer application, management methods, etc.;
- systems-related competency—input, output, transformation, operators, behavior, properties, etc., and
- social competency—general: societal awareness, cultural sensitivity; particular: teamwork, inter-personal skills, communication skills, leadership, flexibility.

In order to achieve these competencies, we must question what aspects and parts of designing, including object and design process knowledge:

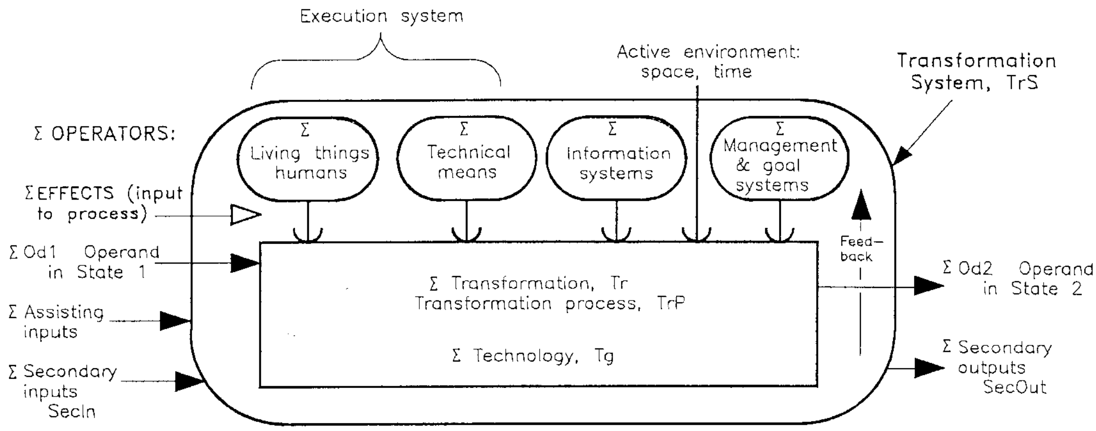
- can be taught and learned;
- can be learned from experience with designing: with prior explanation of context; with simultaneous explanation of context; with *post hoc* explanation of context;
- can only be learned with experience (is practically unexplainable);
- cannot be learned, because it depends on genetic, social and cultural background (diffusion and infusion), environment, motivation, current situation, etc.

How does this relate to relationships among theory, subject and method? The subject in this inquiry is (a) the technical systems being designed, (b) the design processes and the designers, and (c) the educational systems, including the teachers and learners. All three need theories and methods.

As G. Klaus [9] stated in the subject of cybernetics (see also [10]), relationships exist between the subject under consideration (its nature as a product or process), the theory, and method. The theory should describe and provide a foundation for both the behavior of the subject (with adequate and sufficient precision), and the utilized methods (for using and/or operating the subject, and for designing the subject). The method should be adapted to the subject. These three phenomena are of equivalent status. An interplay between subject (phenomenon and/or artifact), theory and method, refined and examined on each other, characterizes normal human and social progress. Quoting Klaus: '*Both method and theory emerge from the phenomenon of the subject*.'

If the theory of a subject-region (e.g. education, teaching, learning, technical systems, designing) is mature, then the method is founded in the theory. The theory describes reality, the method prescribes how the scientific and practical activity and behavior of the humans should occur—not as an algorithm (otherwise the procedure could be automated), but as a flexible guideline or prescription for the operator to follow and use in order to improve the chances of achieving the desired transformation in a better, more rational way, and in less time.

Where no comprehensive theory is available, methods can still be proposed, even where the structure or behavior of the subjects is not completely known (cybernetic interpretation). The method can be characterized as an input/output relationship (the 'black-box' principle, first formulated by Ashby in 1956). We know that corresponding results will be generated when we act on a system in a certain fashion. The theory will



- Transformation (Tr) –– changes certain properties of the operand (as passive member of the process), by mutual interaction between object and means.
- Operand (Od) – WHAT is being transformed? –– object that is being changed in the transformation from an input state to an output state which should preferably be more desirable.
- State –– aggregate (vector) of values of properties (Pr) of a system at a certain time.
- Technology (Tg) – HOW is it being transformed? –– knowledge about the transformation, formulates what effects are needed.
- Effects (Ef) – WITH WHAT is it being transformed? –– means of transformation, actions exerted onto the operand.
- Assisting inputs – necessary energy, auxiliary materials, regulation and control.
- Secondary inputs (SecIn) –– (1) all necessary (desirable) further inputs to the process, and (2) all undesired inputs (disturbances, contaminants, products of the environment that enter as operands).
- Secondary outputs (SecOut) –– mostly undesirable opeand outputs of the process to the enviroment, their nature and composition depend on the chosen technology.
- Operators (Op) – WHO and WHAT delivers the necessary effects (as active member) to the operand:
  - Op (Hu) – living beings, particularly humans, but also animals, bacteria, etc.;
  - Op (TS) – technical (artificial) means, technical systems;
  - Op (InfS) – information systems;
  - Op (M&GS) – management and goal systems (directing, setting and achieving goals);
  - Op (AEnv) – active environment.
- Active environment (AEnv) – WHERE is it being transformed? –– The part of the general environment that as operator influences the transformation (desired and undesirable effects).
- Space –– the main property of the environment (surroundings) of the transformation.
- Time – WHEN is it being transformed? –– time period during which the transformation occurs.

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- Types of effects acting on the operand, secondary inputs, secondary outputs, etc.:
  –– materials; –– energy; –– information (including signals).
- Types of operand, object being transformed:
  –– biological objects (humans, plants, animals, etc.);
  –– materials; –– energy; –– information.
- Structure of the transformation process:
  –– elements = operations (O), or groups of operations;
  –– relationships = connections between the outputs of one operation (or group of operations) with the inputs of the immediately following operation (or group of operations);
  Operations can take place sequentially (in series) or simultaneously (in parallel).

Fig. 2. General mode of the transformation process.

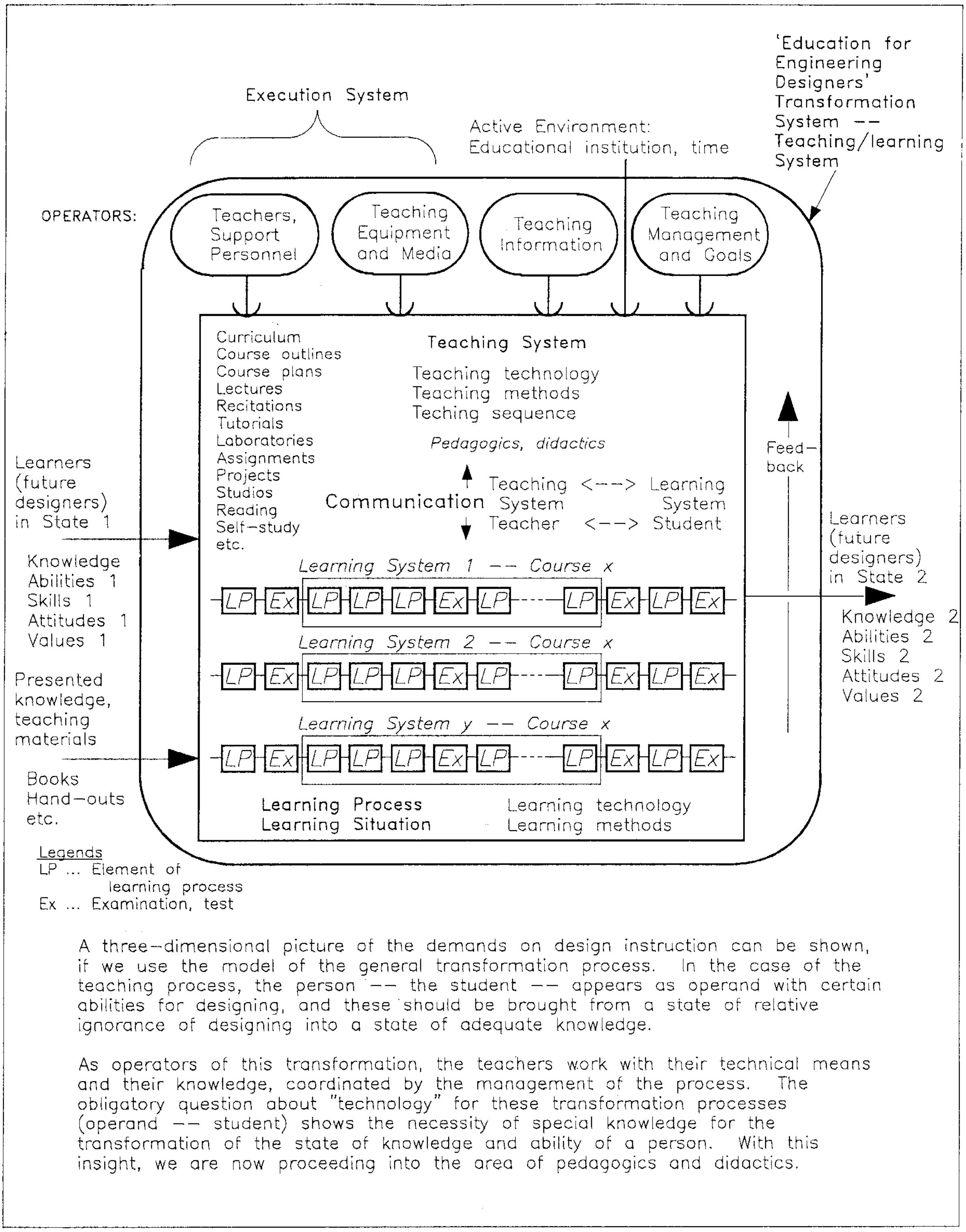

Fig. 3. Model of the teaching and learning process.

then—and often after a lengthy time delay, allowing for research—give an explanation of why this is so.

Also, how does this relate to Design Science [6], the theory of technical systems [11], the theory of design processes [12], and design methodology [13, 14]? These can provide a basis for designing and for education in designing [4]. The many other books about designing should not be forgotten.

And how does this relate to theories and methods of education, pedagogics and didactics? This question needs to be explored in the context of the teaching system, the teaching and learning processes.

TEACHING SYSTEM

In order to define the range of problems of our area, we begin with establishing the model of the teaching system, starting from the general model of the transformation system, Fig. 2. A plastic picture of the demands on design instruction (education) exists if the model of the teaching and learning process is used, see Fig. 3. We see that this process model is derived directly from the general transformation process. In case of the teaching and learning processes the human—the student as an individual or in a group—appears as operand, and possesses certain abilities for designing, who should be brought from the state of 'lacking or insufficient knowledge of designing' into the state of adequate knowledge.

As operators of this transformation, the teachers work with their technical means and their knowledge, in a certain environment, coordinated by the management of the process. The obligatory question about the 'technology' for these transformation processes, whose operand is the student, presents the need for a special knowledge for transforming the state of knowledge, ability and skill of a person. We hereby enter the area of pedagogics and didactics.

We are dealing here with a transformation in which a person (a learner, a student) with a certain level of knowledge, abilities, skills, attitudes, and values, i.e. in state 1, should reach state 2 with a different level of knowledge, abilities and skills, and a different set of attitudes and values. If we start from the general model of the transformation process, then such a transformation is brought about through the influences of a human (a teacher), technical means (instruction instruments, media), information, and teaching management, and through influences of an environment. Of decisive importance is the chosen 'technology', therefore the organization of the process.

Figure 3 presents the teaching and learning system model in symbolic form. Considering the terminology, the students are the operand of the teaching and learning process. The peculiar feature of the teaching and learning process is the active role of the students (as distinct from the passive role of most operands in transformations). Their learning processes proceed during their studies of the subject matter (e.g. object and process knowledge of designing) parallel to the teaching processes, or even outside them. Each student differs (more or less) from other students through a different level of knowledge, through different abilities and skills, as well as through different attitudes and values, among others (although they still have much in common). For that reason, pedagogics regards the learning person as a 'learning system' (a psycho-structure). The teacher in-group instruction (with his/her own psycho-structure) is presented with several different learning systems (psycho-structures). We usually strive for the highest possible homogeneity of the learning groups.

The model also shows **tests and examinations**. At the beginning of an educational experience the tests inquire about state 1, and at the end about state 2 of the learner's knowledge, ability, skill, attitudes and values. Pedagogics, regarded as 'technology' of the teaching/learning process, should now explore the laws and relationships of individual elements, and formulate a theory. One strives for maximum effectiveness, as for any other process.

TEACHING AND LEARNING PROCESS FACTORS

Let us now analyze the individual factors of the teaching/learning system, to discover the range of problems of pedagogics and to ask suitable questions.

Goal of the teaching/learning system: why is teaching needed?

Let us begin with the objectives. In general for students, the accomplishment of state 2 (adequate knowledge and capability of designing) can be set as educational goal. Of course this state must be clearly and accurately defined, in our case with reference to design abilities. We should not forget that each teaching process is a part of the total upbringing and that these wider goals are also inalienable.

Effectiveness as a goal puts further demands on all process factors. Of course the goals differ for individual types of teaching/learning systems, be they for the preparation of the present generation, for detail designers or design engineers, or for further education of engineering designers from the practice.

Design education is mostly a part of the total education, which is contained in the curriculum; education and its methods must be adapted to that curriculum. The decisions about the curriculum—study goals and study plans—are the responsibility of the management of the teaching/learning processes.

Gagné [15] has appropriately characterized the goals of the teaching/learning processes (especially for higher education), namely 'make learning possible', i.e. transmitting of teaching contents, but also providing favorable conditions (see operator 'environment') for the learning systems, the students.

Who will be the learning person (the learning system)—operand of the process?

The question about the input to the teaching/learning processes depends, of course, on the desired output, i.e. the goal of the teaching/learning processes. We are however not only concerned about prior specialized knowledge (**prerequisites**), but also about certain personal characteristics,

1) The principle of TOTALITY demands that for every detail of the subject matter (contents for learning) the context relative to the totality of subjects becomes active. Every subject should be observed and developed from all aspects, should be supported by prior experience (of staff and student), and should indicate the scope of new tasks.

2) The principle of ACTIVITY should bring the students (the learners) into an internalized relationship with the subject matter, such that they are actively confronted by their task with their whole inner unity.

3) The principle of INDIVIDUALITY requires that the educational experience is fitted to the individuality of each student (learner), and should consider the uniqueness in time and situation of the active participation of the student.

4) The principle of CURRENCY is predicated on the fact that the formative action on the student (learner) depends on the current educational situation. The sitation must be considered in light of the subject matter (learning content and form of presentation) that appeals to the student, and under what subjective conditions that student approaches the situation.

5) The principle of RELEVANCE is satisfied when all details are brought into a conclusive and sensible sequence that reveals the truth of the subject matter. A logical closure can also be postulated that tries to achieve a measure of completeness of the subject matter to provide a surveyable orienation and order.

6) The ACQUISITION OF KNOWLEDGE should develop the ability to approach new tasks, and to independently find ways of solving (open- and closed-ended) problems in a planned (methodical, systematic) fashion.

Fig. 4. Principles of education.

psychological and biological, which the candidate must possess for the entry into the teaching/learning system. A related question is intended to be answered by the acceptance examinations (whether set by the accepting institution, or by the prior educational experience), which has to decide about admission of the interested person.

Effects of the teacher—Operator 1

What is taught? The question about the teaching contents is already asked when establishing the curriculum. This is probably a more strategic decision. The concrete selection of teaching content in the instructional situation is a didactic task of the teacher alone.

Design Science [4] recognizes two fundamentally different kinds of teaching/learning content (compare Fig. 1):

- knowledge about the object of designing (the system to be designed);
- knowledge about the design process, including methods and abilities of the designer.

Designing puts particular demands on the teaching/learning process, and especially on the teacher.

Unified treatment? The knowledge about objects includes the generalized appreciation of technical products and processes, their constituents, life cycles, properties, development in time, etc., as outlined in the theory of technical systems [11]. A more specialized kind of knowledge about objects includes the branches or sectors of industry—TS 'sorts' (e.g. cranes, pumps, turbines, domestic appliances)—which should also feature in engineering design education. This should be in addition to the engineering sciences, which deal with the isolated phenomena and principles of technical objects, and their analysis. Despite all differences, the TS families, and the engineering sciences, should be treated from related points of view. The aspect common to all of these is the design activity, which probably needs a separate treatment, but which should also be included in the science instruction and in all design branches (industry sectors, TS 'sorts') on a uniform basis. The biggest problem of education at technical universities, colleges and schools (or in engineering departments at general universities, colleges and schools) is in particular the coordination of all design branches from a uniform teaching principle. Only then will students fully understand designing.

How is instruction accomplished? Technology of the teaching/learning processes

Suitable teaching methods, styles of upbringing, and instruction methodology for an educational unit (e.g. course, lesson) in typical situations are important elements for successful education, and consequently one of the main problems of pedagogics and pedagogical education. Concerning design instruction, two critical points exist:

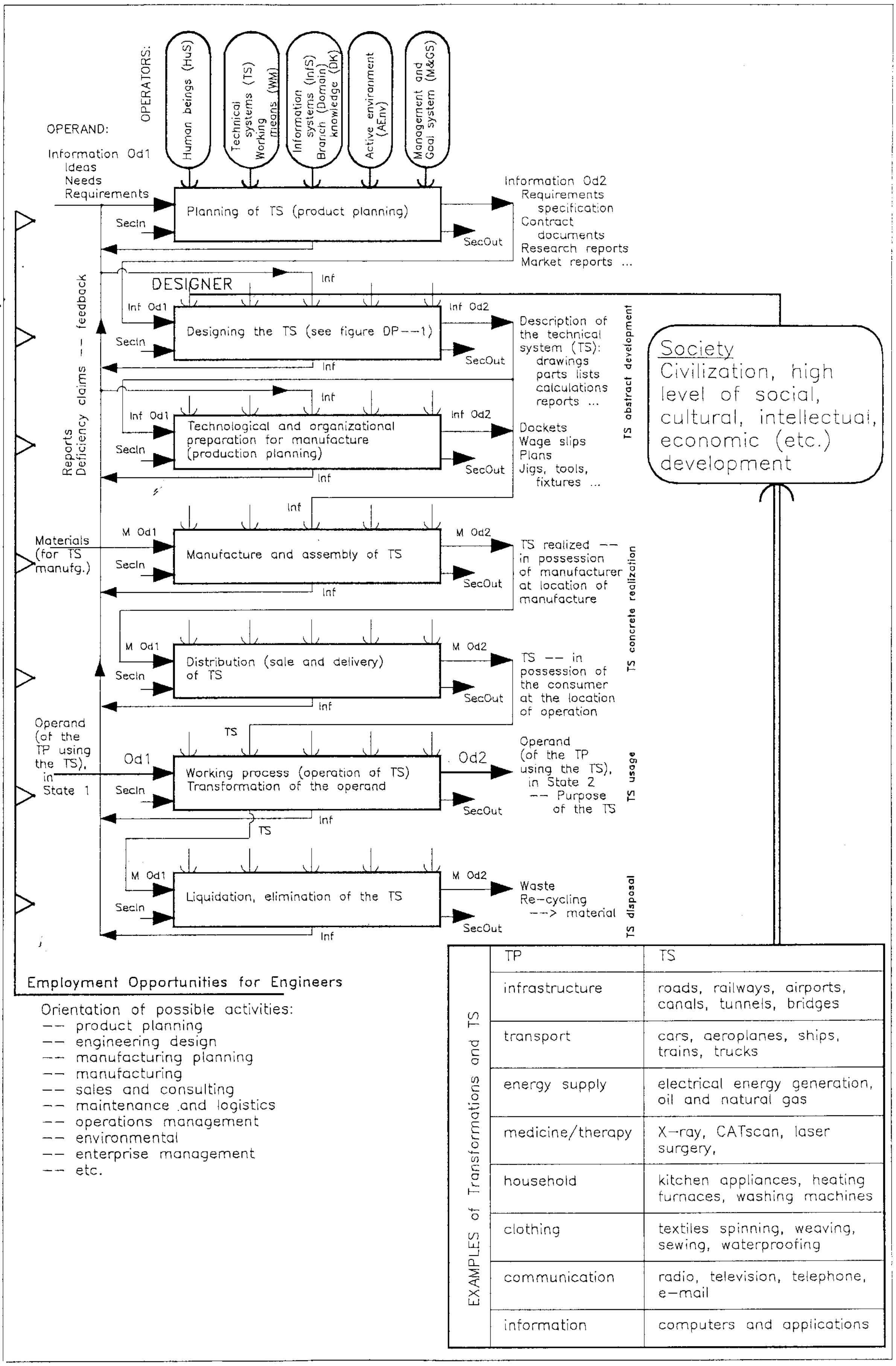

Fig. 5. Engineering and design in societal context.

- there is no experience how an educational procedure can and should be developed following firm rules (first principles);
- design teachers either come to technical universities as proven engineering designers from industrial practice, or they have a post-graduate degree from a university without engineering practice, and probably do not have any education in pedagogical matters.

The decision about the kind of **teaching presentation** belongs also in this area, which already implies certain methods and the role of the teacher. This concerns especially the communication of the teacher with students as learning systems. Individual instruction only involves a two-way communication—teaching system $\longleftrightarrow$ learning system. In contrast, group or parallel instruction involves in addition a communication among the learning systems (students)—collaborative learning.

How often? Even if no reliable method is available for design education, some educational principles are known which can make possible the construction of methods (e.g. see Fig. 4). Important is (among others) the principle of repetition, according to which knowledge can be better captured through repeated presentation and interaction, preferably with some progressive variation in depth, scope and form of presentation and explanation.

Another important question is **when** in the course (teaching process) and in what sequence the individual items of educational content should be presented. Here the principle 'from the known to the unknown' is applicable, but also the principles 'from the abstract to the concrete' and 'from the concrete to the abstract'. The question about the interplay of the analytical (engineering sciences) subject matter (content), the humanities, and the engineering design process knowledge needs to be considered, including how far it is possible and preferably to attempt 'just-in-time' delivery of the necessary related knowledge (an example is described in [16]).

What should be the role of lectures, recitations, practice problems, experiments, projects, etc. individual (Whimbey), pair, and team (collaborative) work, etc., for presentation and acquisition of object knowledge and (design) process/methods knowledge? Is experiential learning and project-based learning necessary, and is it sufficient by itself? An old Chinese piece of wisdom credited to Confucius says:

Tell me and I will forget
Show me and I will remember
Involve me and I will understand
Take one step back and I will act.

In the usual interpretation as separate statements, the first two of this set of items are used to deny the effectiveness of lectures and demonstrations, and to advocate only project-based learning. The last of these items is usually omitted. To us, these statements are best interpreted in combination. Consequently, we would add: *Do all four and I will become competent.*

Effects of the teaching means (media)—Operator 2

With what means? Technical means of various kinds can help the teacher to transmit the teaching contents (object and process knowledge) more clearly, more vividly, more attractively (motivation) and more effectively. The means currently on offer are very abundant and extend from chalkboard through overhead and slide projectors to programmed instruction with teaching machines, from visual and auditory apparatus (including books) to sound film, from calculators to computers and the Internet.

A new situation concerning technical means emerges if, for instance, skills for operating certain instruments is prescribed as educational goal. Examples are engineering drawing with instruments or computers, calculating with computers, experimenting, simulating, etc.

The dominant opinion is that the possibilities which are offered by technical means are not used to advantage, and that favorable chances are neglected.

Effects of teaching information—Operator 3

This operator (i.e. from the viewpoint of the instructing system and its processes) represents the influence of pedagogics (as theory and strategy of education), by means of instruction methods like didactics, pedagogical psychology, social pedagogy among others, to accomplish the desired educational transformation.

The information system also contains the subject matter to be instructed—what is to be learned (as a part of the operand in state 1). For designing, this preferably includes Design Science [6], therefore the Theory of Technical Systems [11] with its constituents: transformation process, technologies, TS properties, structures, modes of action, life cycle, representation, evaluation, developments in time, etc. As an example of benefits that may be found, Fig. 5 shows the representation of a life cycle for a technical system, with an indication of employment opportunities for (educated and trained) engineers, and the mutual effects of transformations and designers on society.

Our goal is to expand the content of design education with the help of questions, and thereby to make possible an efficient procedure of design education.

Effects of teaching organization (management)—Operator 4

The functions of management of the teaching/learning system do not belong directly to pedagogics. They consist of, for example, establishing the goals of the processes through the curriculum, organization including the choice of the operators (teachers, technical means, teaching conditions) and their realization, financial security and operative leadership of the process. However, pedagogics should represent an important aspect in the decisions of the leadership. Thus, for example, in the choice of teachers, their teaching capability should be considered as well as their expert knowledge. Because most engineering branch persons have not graduated from pedagogical education, it is important that part of their continuing education should be dedicated to pedagogics and didactics.

Effects of the environment—Operator 5

When considering the teaching system environment, we must distinguish two classes of environment influences:

a) the direct environment of the teaching/learning processes, for example, a classroom in which the teaching/learning process is executed in material and psychological aspects. This 'atmosphere' is of great importance for the teaching success—the learning that takes place.
b) The macro-environmental conditions, for example, influences of the country, company and economic systems. Apart from the laws governing the teaching/learning situation, some further elements of importance exist for the teaching/learning system, which can influence the teaching and learning process socially or financially (student homes, scholarships, fees, school budgets).

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CLOSURE

As can readily be seen, the subject of teaching and learning for engineering design, especially for the activities of designing, is very complicated. In this series of WDK-HEURISTA workshops held in Pilsen, Czech Republic, we wish to explore, illuminate and clarify the theories and the methods for both object areas (teaching and learning, and designing in engineering) and their relationships. The goal is to develop a rational curriculum and teaching methods, so that we can educate potential designers, and so that they can become effective as designers in the shortest possible time.

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