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EDUCATION FOR ENGINEERING AND DESIGNING

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1. Introduction

Education in engineering is characterized by requirements for several engineering sciences, and for a range of other knowledge. Within this knowledge, designing is usually claimed to be intended as a unifying experience of engineering education. Yet designing is often mis-understood by the academic community. Most academic staff members have not experienced designing in an industrial environment, and many of those people who have such experience can hardly explain it in a comprehensive way.

In most cases, designing is usually treated as ›an art‹, with little guidance about procedure. This may be applicable to consumer products, which are typically mass-produced, and are aimed to please a potential customer by novelty, appearance and other easily assessable factors, the realm of *industrial design*. Customers are expected to buy a tangible product as offered on the market, i.e. to select among available items, all of which have been designed and manufactured prior to marketing. Studio techniques, brainstorming, physical modeling and other similar design procedures are usual. Creativity, ideation and teamwork are regarded as paramount, and formal knowledge about design processes is deemed of little use. An emphasis on entrepreneurship and innovation, and on business matters, is probably of benefit. An appropriate paradigm is that of ›integrated product development‹. Designing, mainly resulting in artistic renderings of a proposed product, is an integral and important part of product development, and needs little specialized engineering knowledge from the designers.

Where technical performance matters, i.e. in *engineering design*, the ›art‹ of engineering is of less use. Creativity and ideation need to be supported by knowledge and methods, and a measure of routine work, which is directed towards achieving an optimal technical system for the intended use. This applies in particular to industrial machinery, whether for manufacturing or for civil engineering construction (etc.), but may also be needed in a durable consumer-product where appearance design is prominent. The machinery must fulfil a (usually well defined and given) purpose, it must function and work effectively, but appearance matters much less. Defining these purposes and functions is usually a task for management and/or a sales department, they determine the product mix offered by an enterprise, and the requirements specification for an individual product (line). Some of these products are designed (as single items, or as small series) for a customer to order, the customer buys a virtual and future product on the reputation of the manufacturing enterprise. Designing needs to re-interpret the given requirements, (a) so that the designers understand the problems, and (b) to incorporate those considerations that the requirements specification does not cover. A careful search for alternative principles of operation and action, modes of construction and manufacture is appropriate, and demands analysis and selection. Yet most mechanical equipment is difficult to analyze by mathematical techniques, unless it is in concept severely simplified. Technical engineering knowledge by the design engineer is an essential component, and designing is usually a separable activity within the product development process (although this may not be acknowledged by the enterprise

managers).
In contrast, electrical and electronic devices are much more easily linearized for analysis and simulation. Civil engineering constructions tend to be more constricted by laws, regulations and codes of practice. Chemical engineering seems to concentrate on the processes that are needed to transform the raw materials into chemical products B the machinery that performs these processes is left to mechanical engineers and contractors. Yet currently most machines are hybrids, with electronic control, mechanical, thermodynamic, fluid, chemical (e.g. combustion) and other phenomena interacting.

2. Problems in Engineering Education

Courses in engineering are mostly taught in isolation, and where possible as analytical, mathematics-based scientific disciplines. Yet the search for alternative solution principles involves searching among all the sciences, and using experience from existing machinery. A better arrangement of engineering science knowledge for designing would be to collect the different principles and phenomena that can deliver a desired output effect B the current scientific disciplines are not suitable for a search for alternatives [Eder 1996].
Humanities are ›tacked on‹ to the engineering curricula as additions, with little thought about relevance and connection to the engineering side. They have generally been seen as ›stand-alone‹ presentations, each course has been treated independently and from the point of view of the specialized interest of the presenting professor. The significance of technical systems for the cultural and social life of ordinary people in almost never mentioned. Yet culture and technology develop in mutual interplay, and technology must be concerned about the values of society.
A ›capstone design‹ course often claims to unify the curriculum by a project, again with little guidance about procedures. Many of these projects are more closely allied to research than to designing. Unification of curricula, and integration of knowledge systems in this way is almost impossible to achieve. It would remain for inexperienced students to recognize the connections for themselves B a difficult task in itself, especially whilst trying to learn the subject matter.

3. Knowledge Integration

Each student must, of course, build up his/her own knowledge system. This includes the internalized (tacit) knowledge, and the knowledge available from the literature, including (e.g.) notes and books that the student makes and uses during education. Any guidance about a suitable system, especially about the relationships among knowledge elements should be useful to students, both as an aid to understanding why the knowledge should be learned, and to encourage its ethical use.
A suitable tool to encourage the necessary integration of knowledge areas is offered to provide a conceptual framework for engineering education. The Theory of Technical Systems [Hubka & Eder 1988], as a constituent of Design Science [Hubka & Eder 1996], contains several explanatory and graphical models that can make the relationships among knowledge areas clearer for students and academic staff. Models of transformation systems and of design situations are probably the most useful in this context.

4. Sciences *vs*. Engineering

In a previous paper [Eder 1995], the author characterized these two important areas of knowledge with reference to the theories of Kuhn [Kuhn 1970,1977].
Sciences, in their research interests, are involved both in producing and in expanding the forefront of the boundaries of a limited area of knowledge. They are not *per se* interested in the existing knowledge of these areas, nor in their mutual relationships, except for the purposes of teaching future researchers. Nevertheless, these individual areas incidentally require a knowledge of the foundations and histories of those areas of knowledge, and a small general awareness of history and the humanities in general.
Engineering has the purpose of creating working artifacts (products and processes) to satisfy the needs of potential customers and users. This is accomplished by designing suitable technical systems. The

knowledge basis for designing lies mainly within the whole collection of existing areas of knowledge. Even new inventions and science spin-off developments must be accomplished with the existing knowledge basis B which for engineering design includes the engineering sciences, but also the knowledge of culture, societal organization, economics, and other areas, at both macro and micro levels.

For many of these areas, the knowledge need not be presented in depth, a general awareness is sufficient. Nevertheless, it is important that the relationships among the knowledge areas are clearly and explicitly indicated during the presentations B sufficient integration is needed. For instance, if a thermodynamic cyclic process is to be used for energy conversion (e.g. chemical to mechanical), the pressure must be contained (strength and mechanics of materials), cooling is needed (heat transfer), energy must be supplied and extracted (fluid dynamics, mechanics, machine elements), etc. Leaving this integration to the individual student is both inefficient and ineffective.

It has been stated that an engineer needs about ten years to become a competent engineering designer for a particular family of technical systems, i.e. the products of his/her employing enterprise. In large part this time is needed for the new engineer to accumulate and integrate his/her knowledge system, including the ›tricks of the trade= (heuristics) about the products and about the design methods and approaches.

Engineers need also to be aware of the functioning of an enterprise within an economic system. Their products must be marketable at an economic rate of return, must be ethically and morally acceptable, aesthetically sufficient to satisfy the customers and users, ergonomic for users and maintainers, etc. Engineers must also work in cooperating teams, i.e. they must have adequate people-skills as well as technical knowledge and skills B these latter are related to working methods that engineers can apply.

As G. Klaus [Klaus 1965] stated in cybernetics, relationships exist between the subject under consideration (its nature as a product or process), the theory, and method. The theory should describe both the behavior of the subject with adequate and sufficient precision, and methods that may be used.

Both method and theory emerge from the phenomenon of the subject

The theory may be expressed in mental, graphical and physical models, verbal explanations, and where possible symbolic/mathematical expressions; it may be formalized, or merely a hunch in the mind. The suitable method may be applicable for using and/or operating the subject, and/or for designing it. Methods are explicit or implied prescriptions, i.e. instructions that may be useful if followed, and which may lead to better solutions, but their use is voluntary.

5. Structure for Engineering Education

A formal structure to engineering education can be proposed which can create a unity by showing relationships among the acknowledged parts of engineering knowledge. This should include not only the engineering sciences, but also the humanities and their relevance to engineering, the relevance of engineering to society and culture, and the procedural aspects of designing and using technical devices B technical systems.

A suitable formal structure to provide a conceptual framework for engineering education is delivered by the Theory of Technical Systems [Eder 1996], a section of Design Science [Hubka & Eder 1996]. This theory, formulated in graphical models and explanations, show how one area of knowledge connects to and affects another, also among the non-engineering subjects. Design Science [Hubka & Eder 1996] consists of *object knowledge* (related to real phenomena and material objects), and *design process knowledge* (related to procedures and methods). Both are presented in appropriate theories and as represented by practical and applicable knowledge (much of which is not supported by formal theories). Design Science [Hubka & Eder 1996] is not intended to include the knowledge of engineering sciences themselves, nor of the humanities, merely to indicate the relationships of designing and these disciplines.

The Theory of Technical Systems [Hubka & Eder 1988] provides several forms of meta-knowledge, which may be summarized as:

- nature of technical systems, and their role in performing (desirable) transformations for the benefit of (a portion of) mankind;

- structures of different kinds of constituent elements that may be recognized within (and across the boundary of) a technical system B constructional elements, sub-assemblies, organs, functions, but also process elements and operations;
- taxonomy of technical systems B hierarchies arranged (e.g.) according to complexity of technical systems B elements, self-contained functional units made of such elements, purposeful machines, plant consisting of machines;
- properties of technical systems B a set of classes of properties that every technical system must carry, but in very different importances and qualities, see further description below;
- evaluation of technical systems B basis for decision making about the suitability of a technical system for its proposed task;
- modeling and representation used for establishing (designing), defining and analyzing technical systems, and communicating what needs to be manufactured, assembled, tested and delivered to achieve customer satisfaction;
- origination and life cycle of technical systems; and
- development in time of technical systems B successive generations.

Each of these has a set of explanations in words and diagrams that generalize the needed knowledge for all technical systems, and that can provide guidelines and methods for product development and designing.

Such meta-knowledge is not only applicable for mechanical engineering. For instance, chemical engineering emphasizes the working (usage) process as a set of needed chemical reactions, but leaves the apparatus and machinery and their control for other engineering disciplines. Naval architecture is mainly mechanical engineering. Some of this knowledge may also be useful for more artistic and humanistic disciplines, e.g. architecture, industrial design, etc.

The classes of properties (see fourth bullet above) as defined in the Theory of Technical Systems [Hubka & Eder 1988] are as follows:

External Properties

1. FuPr Function B desired behavior of the technical system (the target);
2. FDPr Functionally determined properties B parameters, properties conditional on functioning (operating)
3. OppPr Operational properties
4. MfgPr Manufacturing properties B realization properties
5. DiPr Distribution properties
6. LiqPr Liquidation properties
7. HuFPr Human factors properties B ergonomics, esthetics, psychology
8. TSFPr TS-factors properties B in their working process, i.e. acting on the life cycle of the target technical system
9. ISPr Information system factors properties B including law and societal information
10. MgtPr Management and goal factors properties
    B management situation - delivery and planning, etc.
    B economic properties - costs, pricing, returns, etc.
    B time - availability, repair and maintenance time
    B organization - personnel, financing, etc.
    B enterprise environment - social, political, cultural factors, etc.
11. EnvPr Environment factors properties
    B law and societal conformity - regulations, codes of practice, intellectual property rights, legal implications, etc.
    B TS-material - effects on environment
    B TP/TS secondary output and TS disposal

Internal Properties

12. DesPr Design properties

B Design characteristics

B General design properties

B Elementary design properties

In particular, the set of properties listed above can help to ensure full coverage of all considerations that should appear within the design processes. The first three classes refer to the working process of the technical system, i.e. its usage for its intended task. Classes 4, 5 and 6 refer to the conditions that the technical system must withstand during its life cycle, including its manufacture. Classes 7 to 11 (inclusive) refer to human factors, available information, enterprise and (inter)national economics, and cultural and societal conditions.

Designing in engineering, the process of thinking out a technical system (i.e. before it exists in reality) in concepts, layouts and details, and exploring the available alternative solution proposals to select an optimal system for its intended purpose, consists of establishing the internal properties (class 12) in such a way that the (11 classes of) external properties are satisfied. These internal properties consist of three sections

- the design characteristics which contain the principles of operation and construction applicable for a family of technical systems (e.g. power transformers, cranes, machine tools, etc.), including any heuristic advice and values;
- the general design properties that are mainly analyzable with the help of the engineering sciences; and
- the elementary design properties that consist of the precise manufacturing definitions, geometries, dimensions, tolerances, surface conditions, (etc.) of all constructional elements and their interconnections.

On the basis of the (abstract) object knowledge contained in and associated with the Theory of Technical Systems [Hubka & Eder 1988], various procedures and methods can be recommended to assist in designing, i.e. the design process knowledge B which includes, but is not restricted to, creativity.

6. Curriculum Recommendations

Explicitly teaching the Theory of Technical Systems throughout the years of engineering study, at an appropriate level of detail, should give students a sufficient level of understanding of the reasons for studying each individual subject (course) [Eder 1999]. In particular, consideration of the general design properties involves the engineering sciences. Engineering graphics is needed for the elementary design properties. Machine elements, mechanics of materials and the other engineering sciences are needed for the design characteristics. The curriculum should include a survey of the design principles, alternatives, and manufacturing for at least one family of technical systems as actually designed and used. These are the main constituents of engineering object knowledge that future engineers need to learn. The Theory of Technical Systems [Hubka & Eder 1988] also obviously connects to the non-engineering subjects B the external properties indicate the reason for including an exposure to the humanities, interactions among technology, science, arts, sociology, psychology, etc. But this demands that all courses are explicitly cross-referenced to one another by each instructor B a difficult task for the teachers and for the administration.

Designing can only be successful if the needs and requirements from engineering sciences, manufacturing methods, societal needs, economics, and other areas (i.e. the properties of technical systems) are adequately balanced. This can most effectively be achieved if a systematic approach to designing is used B preferably based on the Theory of Technical Systems adapted for designing, and recommending appropriate methods for the achieved progress in designing [Eder 1996, 1997]. Of course, teamwork needs emphasis, especially for such products that need to combine appearance and technical functioning. The team members will include artistic designers, manufacturing experts, sales and marketing experts, etc. Nevertheless, the engineering designer will be expected to shoulder the responsibility for the product.

The purposes and constraints of designing, and the needed tacit and recorded knowledge of objects and of processes are also easily explained. Because designing must accommodate all phases of the life cycle, and must provide an adequate (preferably optimal) set of properties for the product, a certain amount of structuring of the design process is also preferable. This involves design methods, which are especially useful for conceptualizing a product. Conceptualizing should be done before any layout is attempted, especially if computers (CAD/CAE) are to be used for representation of the system being designed.

7. Closure

Justifying the recommended design methods is easily achieved with the help of the Theory of Technical Systems. It is therefore useful in teaching and learning about engineering design, and supports the creativity of the designer [Eder 1996]. Awareness of this theory is a good guideline for achieving integration of knowledge systems and for unifying an engineering curriculum.

I have used these theories and the appropriate design methods for at least ten years, explicitly presenting them in lectures and pre-printed material, in my design courses in Mechanical Engineering at the Royal Military College of Canada. I also run mini-projects within the design courses, continually monitoring the progress of student teams, and providing added explanations as needed. Reports from other academic staff members confirm that students use the methods in other courses, especially in their final-year project.

The Theory of Technical Systems should be considered by engineering departments as a valuable integration tool for engineering education. Academic staff teaching courses for engineering students should become sufficiently familiar with this body of theory to give guidance to engineering students about suitable structures for a more effective system of knowledge.

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