Integrated Engineering Design Research and Interdisciplinary Education in cooperation with Industrial Partners

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ABSTRACT

Creative engineering design activities and their management in research, education and practice generally conflict on the one hand with ‘instruction’ based methodical approaches because of their prevailing rigidity, and on the other hand with ‘math-logic’ based theoretical approaches due to their extreme abstractness. A developed and validated approach based on the Theory of technical systems (TTS), a constituent of Engineering design science (EDS), which brings significant benefits in all the above mentioned creative fields including their important mutual context is outlined in the paper.

Keywords: Engineering Design Science, Designing, Creativity, Technical Products, Technical Systems

1. INTRODUCTION

Usual approaches to design engineering of technical products tend towards traditional, intuitive ways of using the knowledge, which have been acquired both from theory and (more and more in the course of time) from practice. Practising engineering designers in general ‘do not like’ the more systematic approaches, because of their ‘rigidity’, which they find to be incompatible with their own creativity.

It is also obviously not effective and efficient to load the memory of practising engineering designers and engineering design students with acquiring engineering design knowledge exclusively in their specialised forms. They then need to use a great deal of their creativity for painstaking step by step discovery of analogies and applications of such specialised forms within the area of their work.

Usual instructive methodical approaches to engineering design procedures improve this situation. But if they are considered by themselves, they resemble more formal algorithms, rather than the needed ‘handy workbench’ of knowledge and tools for the creative work of engineering designers.

There is no doubt that this situation also negatively influences the understanding of engineering design students regarding connections among the many subjects of their studies, the time needed for the ‘ripening’ of engineering design novices, and even the flexibility of many skilled practising engineering designers. We would like to introduce how this situation can be dealt with in order to obtain better results in engineering design research, education and practice.

2. TECHNICAL PRODUCTS AND THEORY OF TECHNICAL SYSTEMS

Technical products

Technical product (which stresses ‘production view’ in the ‘practice realm’) can be understood as a synonym for Technical system (which stresses ‘system view’ in the ‘theory realm’). Technical system (TS) is a category of an artificial deterministic system that performs the necessary effects for transformation of an operand in a process [12].

Technical products are increasingly complex, complicated and advanced in order to be able to satisfy the ever growing demands put on them. There is a huge set of TS properties that are required, and engineering designers must be aware of them. These are not only requirements concerning the TS operation functions, their parameters and connection interfaces, but also a high level of product safety and health protection, good appearance, easy manufacture, transport, maintenance and liquidation, low price, short delivery time, and many other factors.

Products in general as well as Technical Products are more and more consciously understood (in the case of Technical products also designed and treated) as heterogeneous products, like e.g. mechatronic products. Coming from [12] and [15], heterogeneous products in general can consist of hardware (solid material), ‘formlessware’ (fluid material), software (information), ‘energyware’ (energy), ‘assistanceware’ (service), as well as ‘livingware’ (living beings, from which are excluded human beings for ethical reasons) [6].
The aim of theoretical, i.e. descriptive knowledge related to TS (Theory of technical systems - TTS), is to classify and categorize the knowledge about (existing) technical products/systems (TS) into an ordered set of statements about their nature, regularities of configuration, development and various empirical TS-related observations [12]. In the following is outlined our current view on a concept of the fundamental knowledge of TTS which supports and integrates the whole framework of Engineering Design Science (EDS) in context with [13] [3] and [4] [3] is used to refer to all four books [12], [13], [3] and [4] in the following if appropriate.

Transformation system

The Transformation system [3] is an axiomatic abstract general model of a system aimed at any artificial change (Fig. 1). The transformation is performed by five transforming “object” constituents called Operators (Human & other living beings system - HuS, Technical means - TS, Active and reactive environment - AREnv, professional Information system (IS), and Management information system (MgS) [3]. They perform a required artificial change of a state of an above mentioned Operand, by their direct and/or indirect exerted active and/or reactive effects. Operand can consist of material, energy and information or can be living beings [3] Transformation is usually aimed only at one of the constituents. Remaining transformations, if any, only accompany them.

The power of the traditional model of Transformation system can be simply enhanced by adding ‘Auxiliary transformation (sub)systems of Operators’ services’ (Fig. 1) (HuS - staff training, TS - maintenance and repairs, IS and MgS maintenance). The model of TrfS serves as a tool for modelling either real artificial transformations of any kind and complexity or as an element of the more complex EDS models of higher hierarchical levels as outlined in the following sections.

The usually considered model of TS Life cycle consists of significant TS Life stages: Planning, Designing, Technological and organisational preparation for manufacturing and other TS LC stages, Production (incl. manufacturing and assembly), Distribution (incl. packaging, sale and delivery), Operation (incl. maintenance) and Liquidation (incl. disassembly and recycling). In comparison to the traditional model, we consider information outputs from all preceding TS LC stages as inputs to the Operators Information system of the respective following Transformation systems.

Fig. 2 General model of TS Life cycle

Note also that information outputs from the respective processes work as inputs to the operators Information System of the following Transformation systems. The reason is that this information works as indirect transformation effects in the form of constraints, not as input of the following Transformation processes (i.e. transformed Operand) as has usually been considered up to now. The next difference consists of our more general definition of the LC stage “Technological and organisational preparation for manufacturing” also for preparations for all LC stages following Manufacturing.

TS properties

TS Property is any TS ‘feature, characteristics, attribute, etc.’, such as: power, form, size, stability, durability, colour, manufacturability, transportability, suitability for storage, etc., which characterize TS [11]. Thus TS Property can be understood as an inherent (i.e. ‘inborn’ during design engineering) ‘unchangeable’ TS attribute/characteristic [15] which corresponds to a requirement regarding a specific viewpoint. Any TS Property can be specified, measured, compared and finally evaluated by using a set of either numerical or textual ‘values’ of either a chosen or normative set of the appropriate TS Property indicators [10].

TS Properties can be classified in a number of ways. The described consistent and transparent hierarchical taxonomy stems from [12] and our research supported by inquiries and by our large university and industry related experience [9]. TS Properties are split first into the following three Domains [10]:

(1) Descriptive properties comprising a description of TS itself including its descriptive features/characteristics.

(2) Reactive (behavioural) properties comprising reactions/responses of TS to its external and/or internal load/stimuli of any kind during TS Life Cycle.

(3) Reflective properties comprising TS reflections of external bodies on TS, i.e. on its Descriptive, Reactive and also ‘reflected’ Reflective properties.

Fig. 1 General model of Transformation system (TrfS) incl. auxiliary systems for service of Operators

TS Life cycle (LC)

A transparent and consistent General model of TS Life cycle (Fig. 2) can be built from a sequence of general models of Transformation system (see above) concretized for the respective TS Life stages [3].
TS Reactive (behavioural) properties are being commonly merged together with Reflective properties. However, it denies their cause-consequence relationships and dissuades engineering designers from using TS Reactive properties as means to fulfil objective requirements. For example a customer needs a machine tool to be ‘precise’, not stiff as is often required / believed. Although stiffness is the most frequent way of achieving TS machine tool precision, it is not the only method and, actually, it is not a sufficient condition (i.e. TS property) to achieve it.

The Domain of descriptive properties is axiomatically structured into 2 classes of Elemental and Feature (Intrinsic in [3]) Engineering design properties [12]. The Domain of reactive (behavioural) properties can be ad hoc structured according to the corresponding scientific and/or profession fields [7]. Taxonomy of the large Domain of reflective properties can be appropriately simply split only into 7 Property classes following the structure of the above outlined model of the TS Life cycle (Fig. 2) [7]. These are split into subclasses, like e.g. ‘Human (operator) related properties’ (in all TS LC stages!) into ‘value ones’ (ethic, religion, prejudices, etc.), ‘danger ones’ (safety, ergonomy, hygiene, etc.), transiting to ‘pleasant ones’. (appearance, noise, aroma, etc.).

In our view [7], TS quality is simply understood in concordance with the philosophical category (quality in contradiction to quantity) as a judged set of stated, obligatory, generally implied requirements [15], and possibly a company’s specific requirements on inherent/inborn TS properties. Inherent TS properties are those (e.g. TS form, function, manufacturability, etc.), which cannot be artificially changed by assignment in the following phases (like e.g. TS price, owner, etc. can).

Quality thus represents a judged agreed and/or stated set of criteria for TS evaluation (based on the total evaluation of the respective required values of TS Property indicators compared with the corresponding predicted or existing ones) which results in a value of TS quality [7]. For a designed TS it is possible to deal with predicted “Product design (i.e. inherent) quality” of its Constructional structure, which has not yet been ‘distorted’ by real market evaluations considering factors of a real business situation (e.g. company prestige and/or popularity, provided services, accessibility of spare parts, power of competitors, etc.). By adding the predicted delivery cost and time, and predicted business factors the corresponding TS Product design competitiveness and Product business competitiveness can also be predicted and treated [7].

Taxonomy of DfX and PoX knowledge and methods
The developed taxonomy system of TS properties can also serve as a direct basis for the taxonomy of ‘Design for X’ (DfX) and ‘Prediction of X’ (PoX) knowledge and methods (where X usually means a TS property class, subclass, sub-subclass or a property respectively) [2], [3], [5] and [14].

This has also brought a quite new systematic, transparent and user-friendly view to this huge, very important, however, traditionally very fuzzy area of supporting engineering design knowledge, methods and tools again. These results, which include the relevant basic knowledge, related to all property classes above have been applied in our university teaching texts, but have not yet been published.

3. KNOWLEDGE INTEGRATED DESIGNING

Four levels of mutually bounded key approaches for problem solving focused on designing can be recognised (Fig.4):

(0) The ‘Trial and Error (and Success)’ based strategy can be assumed to be a ‘zero’ level for problem solving. A series of trials (attempts) should find the solution by individual steps. Appraisal (evaluation) of the suitability of the solution for the situation is then necessary. Achieved quality of results and required cost and time are accidental so there is possibility exists that no result could be found in this way. Perhaps the only advantage is that ‘almost no’ previous knowledge and experience of the problem to be solved is required in a limit case. The repeated use of ‘Trial and Error’ methods results in some experience, i.e. practical knowledge which could serve as a basis for the higher levels of design problem solving. These levels could be structured roughly as follows:

(I) The ‘Intuitive’ based strategy which usually stems from previously acquired knowledge and experience.

(II) The ‘Instruction’ based strategy, mostly in a form of prescriptive or normative guidelines, which usually stems from summarised general knowledge, special theories and practical experience of their authors, arranged and presented differently (often mnemonicly if possible to simplify their memorising).
The ‘Theory based strategy’ stems mainly from a framework of theoretically based structured knowledge – Engineering Design Science (EDS) - obtained by scientific ‘mapping’ both from theory and practice.

Of course each mentioned subsequent ‘higher’ hierarchical level includes the ‘lower’ level(s), and the real situation is in any case rather vague. When analysing the compatibility of these four strategies, i.e. possibility of flexible use of an optimal level appropriate to the solved problem, we can easily find great discrepancies among instruction level II and theoretically ‘lower’ levels I and 0. The reason is that principally quite ‘rigid’ instruction level II hardly provides designers with needed flexible support when returning from levels 0 and I back to level II (Fig. 4, middle).

It is obviously one of the main reasons for the above mentioned difficulties in the acceptance of the instruction approaches in practice. However, theory based level III, which provides designers with a transparent system ‘map’ of theoretically based knowledge on (and for) design engineering is very compatible with all lower levels, enabling the ‘correct’ location in this ‘map’ to be found easily after returning from the ‘lower’ levels (including instruction level II) (Fig. 4, middle top).

Our research, supported by industrial and academic experience and the feedback gained during cooperation with industry, proves that the generally used approaches to design engineering, which are ‘Trial and Error/Success’ approach, ‘Intuitive approach’ and ‘Instruction approach’ are deficient in many aspects for current and future needs. We find that a theory (Theory of Technical Systems [12]) based integrated design problem solving approach, which we call multilevel Knowledge Integrated Designing (KID), is a very powerful vehicle for treating dialectic systematic and at the same time creative design engineering including its management.

It enables the most appropriate and consistent use of all the mentioned problem solving strategies, because the theory based engineering design ‘map’ of knowledge spans/cover the other ‘lower’ hierarchical levels (Fig 4). Thus engineering and industrial designers, and both ‘outside’ leaders and executive ‘inside’ ones, as well as necessary cooperating specialised experts can manage, solve and monitor their projects on the theory based level. It enables them to ‘jump’ to other ‘lower’ levels at any time if efficient and effective, and again to ‘return’ back to the ‘map’ to follow the planned strategic path. However, TS Design Specification, Evaluation of alternatives and variants of any output for optimal Decisions, as well as Documentation including its archiving and transfer to other TS Life stages ought to be almost exclusively systematic (Fig. 5).

We have experienced that the ‘KID’ approach helps to integrate the individual specialists within the interdisciplinary teams very effectively [9]. We have also experienced and validated that when any designer mastering the ‘KID’ concept it is naturally converted into a dialectic ‘systematic heuristic’ way of design thinking which can be metaphorically called ‘Knowledge Integrated (systematic creative design) Thinking (KIT)’ (Fig. 4, right).

3. APPLICATIONS

The consistent system of engineering design knowledge and methods both from theory and practice (Fig. 5, in the middle) based on and integrated by the theory of technical systems (TTS) outlined above has been continuously verified and compared to other approaches and gradually improved and validated in executive and also in management activities in a number of our projects performed mostly in cooperation with industrial partners. In the following sections, we present a few typical examples of this.

Applications in research for industry

One of the applications has been the Information and evaluation database system for Constructional specimens from conventional (solid) and unconventional (composite) materials (CSM). Implementation in MS Excel SW has capacity for 34 variants of 4 types of specimens, and 270 property indicators for each recorded specimen. Due to the full consistency of the database, the system has also enabled a method to be developed for comparing numerical values of any two property indicators of the same type (e.g. for a bending displacement) for any two specimens independent of their constructional structure, type of load and/or border constraints.
The potential of TTS for management and conceptual design engineering can be illustrated with two larger applications. The Information and evaluation database type sheet systems for Regional rail vehicles (RRV) [8], and for City tram vehicles (CTV). Two user-friendly implementations in MS Excel SW (Fig. 7) have been developed for 49 variants of 20 RRV types from 10 world producers with 180 property indicators for each recorded RRV, and for 80 variants of 68 CTV types from 5 world producers, 260 property indicators for each recorded CTV respectively. The databases helped to indicate SWOT and new trends for innovations about 5 years before they have been asked from industry to be investigated.

Fig. 7 Information and evaluation databases for Regional railway vehicles (RRV) and City tram vehicles (CTV)

Another significant application for design projects in education and industry is substantially innovated management and an engineering design software tool, which supports product design specification and evaluation of its fulfilment (including generation of risk indicators) as well as prediction of design and business competitiveness of a designed product regarding the former and selected comparable products on the market [7]. All results are depicted in a form of diagrams.

Promising results have been also achieved from a developed method and a SW tool based on the principle of case-based reasoning, enabling prediction of an unknown property indicator value (e.g. cost) for a (e.g. designed) technical specimen of ‘any kind’ (e.g. technological feature, the mentioned material specimen, machine element). This approach is more precise especially in case of not smooth courses of the treated values of property indicators, and immediately takes into account each new downloaded specimen without any re-calculations compared with e.g. traditional regression approaches.

Applications in education and projects for industry
Further results based on the introduced knowledge have been achieved and its usefulness proved in the design education and its management at the Department of Machine Design, UWB. The Engineering Design Science knowledge has been reflected in the complex curriculum model at our department. Constituents of this knowledge have been applied in more than 10 engineering design courses.

Comprehensive work on generally applicable TTS knowledge and methods has been carried out especially in the field of Machine Elements. It concluded with two monographs in Czech, partially available also in English. These works introduced an innovative approach of classifying general and specialized Machine Elements exclusively according to their functions and working principles, and of the fully consistent structure for description of knowledge and methods relevant to any hierarchical level and type of Machine Elements.

Further results and valuable feedback have been achieved in ‘property driven designing’ of technical products within the outlined framework of TTS based KID concept outlined above.

Since 2004 this philosophy has been utilised and validated in more than 120 student teams (from 6 to 8 students each) on 25 very different topics of the interdisciplinary engineering and industrial design projects assigned consulted and evaluated by 13 Czech and foreign industrial companies (Fig. 8, 9 and 10). Each year the projects were performed from scratch within 13 weeks of the winter term by engineering design and management students from our Faculty of Mechanical Engineering together with industrial design students from Institute of Art and Design, and consulted by physiotherapy and ergo therapy students from Faculty of Health Studies, and also selectively supported by students from our Faculty of Electrical Engineering, from University of Zielona Gora (PL) and University of Deggendorf (G) (Fig. 10) [9] and [10].

Fig. 8 Minutes from consultancies with partners experts, and from competitive and workshop student presentations

Fig. 9 Samples of results of student engineering and industrial design projects assigned, consulted and co-evaluated in cooperation with industrial partners
Here the important role of the presented approaches lies not only in support of designing itself but especially in supporting both explicit (leading) and implicit (executive) engineering design management tools for project activities as a whole, in continuous evaluation of the developed technical product from the very beginning to its very end, and for transparent and comprehensive project documentation and presentation.

The projects are the complementary part of the undergraduate master course System design engineering of Technical products, which aims to provide students with foundation in the system of EDS knowledge about and for system management and creative design engineering of technical products. Finally, the TTS based property driven designing has been also more or less applied in a number of university engineering design diploma theses, which have been undertaken for dozens of industrial companies and successfully evaluated by their reviewers.

4. CONCLUSIONS

The introduced approaches, knowledge and methods create an advantageous systematic management and engineering design framework, which enables to adopt ‘any’ reasonable combination of the key design problem solving strategies which we consider to be theory, instruction, intuition and trial & error/success based approaches. It can serve as a powerful foundation for research, education and industrial practice.

We have applied and validated it in a number of projects including development of innovative professional CA software and relevant educational tutorials. The most complex project deals with interdisciplinary team student engineering and industrial design projects assigned, consulted and co-evaluated in cooperation with industrial partners. Students’ outcomes have also resulted in certificated utility and industrial models. The achieved results are very appreciated by participating industrial and institutional partners as well as by design community and our university officials.

We have managed these interdisciplinary projects for 9 years and among others we have experienced that these to be the best practice in educating students for industrial practice. It has always been our important goal in design education to bring design students closer to industrial practice and provide them with experience which they will need in their future jobs. The whole bulk of interdisciplinary student projects also evoked further educational, R&D and business projects performed with institutional and industrial partners.

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REFERENCES