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HARDWARE, SOFTWARE, PROCESSED MATERIAL AND SERVICE CONSTITUENTS AS CONSISTENT ELEMENTS OF A DESIGNED TECHNICAL PRODUCT

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ABSTRACT
Four generic product categories, i.e. ***Hardware***, ***Processed Materials, Software****,* and ***Services*** specified in [14] mirror the increasing share of non-mechanical constituents in recent products. However, traditional design methodologies have until now mostly been focused on mechanical constituents. The recently published guideline for mechatronic systems [15] includes mechanical, electrical and information technology design procedures, however no explicit joint model of the designed technical product integrating these three 'domain specific' parallel streams is presented, and no ***process*** and ***processed material*** constituents are (explicitly) considered in it. The paper will outline a concept for the consistent design engineering of technical products, comprising all the above mentioned generic categories, which is based on the Theory (T) of Technical Systems (TS) [8]. Using TTS, all the above mentioned generic product categories can be specified [5] as consistent elements of the model of the transformation system (TrfS) [8]. In addition, each of the categories also has commonalities or at least analogies in models of both their abstract and abstract topological structures with those of the TS structures. These two basic common features have resulted in a consistent concept for a model of the designed heterogeneous technical product comprising constituents of two or more of the generic categories above. This theoretically based model can then be advantageously used e.g. as an integrating basis during iterative concretisation of the designed technical product according to the procedural models e.g. [9], [11], [12], [13], [15] or even traditional ways with the 'best (and even worse) practice' engineering design strategies [7].

Keywords: Technical Products, Technical Systems, Design Engineering, HW, SW, Processes, Processed Materials, Engineering Design Science

1 INTRODUCTION
Traditional engineering design methodologies have mostly been focused on the mechanical constituents of the designed technical products. This has also been reflected in the related educational approaches and increasingly criticized e.g. [1], [10]. In addition these methodologies have mostly been procedural based [7], i.e. focused predominantly on the engineering design process and its elements themselves. Therefore the stages of the designed technical product are then described mostly formally, using instead the vague names of their representation e.g. conceptual scheme, preliminary layout, etc.
Four generic product categories specified in [14] mirror the increasing share of non-mechanical constituents in recent products:

- 'solid' ***Hardware (HW),*** which is generally tangible and its amount is a countable characteristic;
- 'non-solid' ***Processed Material (FW) - 'Formless-ware'*** *(*according to the proposal of the author), which are generally tangible and their amounts are a continuous characteristic;
- ***Software (SW),*** which consists of information and is generally intangible;
- ***Service (AW) - 'Assistance-ware'*** *(*according to the proposal of the author), which is the result of an activity (i.e. process) performed at the interface between the supplier and customer and is generally intangible.

There may be objections to the ISO classification above, nevertheless it is a point-of-fact that the above mentioned generic categories of products exist, and also concern technical products as shown in the examples concerning the product ‘automobile’ in chapter 2. One of the main objections could be, for example, that no ***‘Energy-ware’ (EW)*** is directly considered, and thus it should be obviously substituted by other categories like Hardware (e.g. battery), Processed materials (e.g. fuel) or Services (e.g. supply of electricity or gas).
The German Society for Engineers has recently published a guideline for mechatronic systems [15], which includes a ‘V-model’ of engineering design development (Figure 1). The domain specific procedural mechanical, electrical and information technology (IT) engineering design procedures/models, are included here in its connecting central ‘bottom part’ labelled ‘domain-specific design’, which is situated between the two ‘V arms’. These arms represent ‘System design’ and ‘System Integration’ processes. These are horizontally connected by verification, validation, and property check feedbacks at different ‘levels’ of maturity of the designed mechatronic product. However, no explicit joint model of the designed technical/mechatronic product that integrates these three ‘domain specific’ parallel design streams is presented, and no processed materials and services constituents are (explicitly) considered in it. A model is shown in [3] similar to [15] with respect to software systems [4].

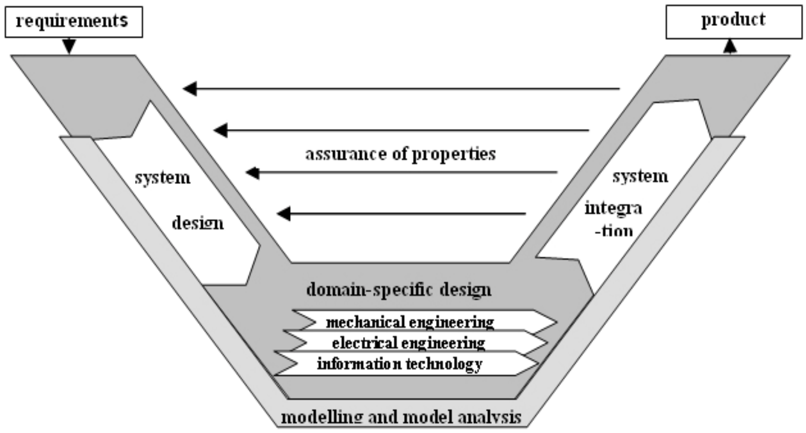

Figure 1: General V model as a macro-cycle of the generic procedure for designing mechatronic systems [15]

Many products comprise elements belonging to different generic product categories. Whether the product is then called ***Hardware, Processed Materials, Software*** or ***Services*** depends on the dominant element [14]. In general each of these elements may or may not be a technical (sub-)system with a substantial contribution from engineering. We will focus here on heterogeneous technical products, comprising in general all the above mentioned generic product categories, the ***basic system*** [15] of which is however dominantly hardware based. For the sake of compatibility with [8], we will call a part of a technical product consisting in general of the first three categories a ***Technical System*** (TS). To stress the general system view of a heterogeneous technical product consisting both of tangible (HW and FW if any) and intangible elements (SW and/or AW) we will call it a ***Heterogeneous TS*** (HTS).

2 HW, PROCESSED MATERIALS, SW, AND SERVICES AS HTS ELEMENTS

Engineering design methodologies can be boosted by implementing a consistent approach based on the Theory of Technical Systems (TTS) [8] to all the above mentioned objectively existing generic categories of technical products. This consistently implemented concept in comprehensive engineering design theory [9] has already proved its power of theory and application in a series of publications [2] by its authors, their colleagues and followers, including the author of the presented paper e.g. [6], [7] and many others.
Using the concept of TTS, we can at first clearly specify all the above mentioned generic categories of technical products as consistent elements of a heterogeneous TS. We will preferably look at these categories as elements of a ‘compound’ technical product. Their splitting up into the respective corresponding partial ‘single category’ products is then only a formal step [5]:

- ***TS hardware (HW):*** the generally tangible, material constituent of TS, the quantity of which is countable; (e.g. mechanical engine part, tyres);
- ***TS processed material (FW):*** the generally tangible, material constituent of TS, the quantity of which is not countable and can be measured only in 'bulk' units of volume, mass, energy, etc. (e.g. fuel, cooling liquid);
- ***TS software (SW):*** the generally intangible, information constituent of TS (e.g. driver's manual), which also includes a set of computer instructions (e.g. engine control software), carried either on embedded or transmission material media, i.e. on the corresponding TS hardware components;
- ***TS service (AW):*** the generally intangible constituent of accompanying TS in the form of a result of a process, which is provided by a supplier to a customer (e.g. operating instructions given by the salesman);

At this moment all these constituents can be specified as elements of the TS Life Cycle (LC) depicted in Figure 2 modelled as a series of structurally identical Transformation Systems (TrfS) shown in more detail in Figure 3 [8]. This is essential for comprehensive specification of the requirements on all 'TS-External' (i.e. 'TS-outside reflective') LC requirements on properties and corresponding behaviours of the designed technical product, and for their establishment and realization by 'TS-Internal' (i.e. 'TS-inside reflective') properties during 'TS-origination LC phases'.

From the viewpoint of the '***TS-existence (and liquidation)'*** domain of the LC we can now see that:

- ***TS hardware*** (HW) is a part of the TS-operator (i.e. one of the subjects performing the needed TrfP) of the Operational Process, which has traditional 'solid' constructional structure as usual;
- ***TS processed material*** (FW) is a part of the TS-operator of the Operational Process, which has a 'non-solid and dummy' constructional structure; which consists only of 'formless' materials;
- ***TS software*** **(SW)** is a part of the TS-operator of the Operational Process in the form of:
  - 'computer' algorithmic and programmed SW carried on either transmission or embedded 'computer' HW.
  - 'traditional' formalized SW, carried on either transmission carriers like paper, stickers, etc. or on embedded inform. carriers like TS labels, lettering, but also TS shapes, colours, etc.
- ***TS services*** **(AW)** are transformations (Figure 3) provided on TS e.g. during/by distribution (sale, delivery, installation, etc. services), maintenance (after sale both guaranteed and non-guaranteed repairs, spare parts delivery, upgrading, etc. services), and, possibly, liquidation (disassembly, separation, recycling, disposal, etc. services) for the respective customers; the technical product in question thus becomes TS-operand (i.e. object of transformation changes within the corresponding TrfP) within these processes.

From the viewpoint of the ***engineering design description of these elements for realisation and existence stages of LC*** we can now see that:

- ***TS hardware*** is completely described by its component [8] (or more recently building [15] or constructional [5]) structure, i.e. by values/manifestations of property characteristics of its Elemental Design Properties; (i.e. of the TS constructional elements and their arrangement, and the respective elements by values/manifestations of property characteristics of their forms, dimensions, materials, types of manufacturing, tolerances and surface qualities – everything in general in pre-assembly and post-assembly states);
- ***TS processed material*** has no 'solid' forms, but its 'constructional structure' can also be described by the property characteristics of the remaining TS Elemental Engineering Design Properties, maybe in a slightly modified form (e.g. elements – constituents, dimensions - volume, etc.);
- ***TS software*** 'constructional/design structure', i.e. structure of 'SW (information) constructional organs,' can be described analogously like TS hardware 'constructional/design structure', i.e. by SW hierarchical elements (e.g. commands, routines, objects) and their arrangement, and their final corresponding forms, i.e. in 'traditional' written symbols (differing according to their type, form etc.), in the form of computer programmes (differing again according to their type, form, language, etc.), and maybe in other 'constructional' forms;
- ***TS service*** can be described as a required change of the state of the TS 'constructional/design structure'. It is 'manufactured', i.e. realized e.g. during the respective LC transformation processes mentioned above.

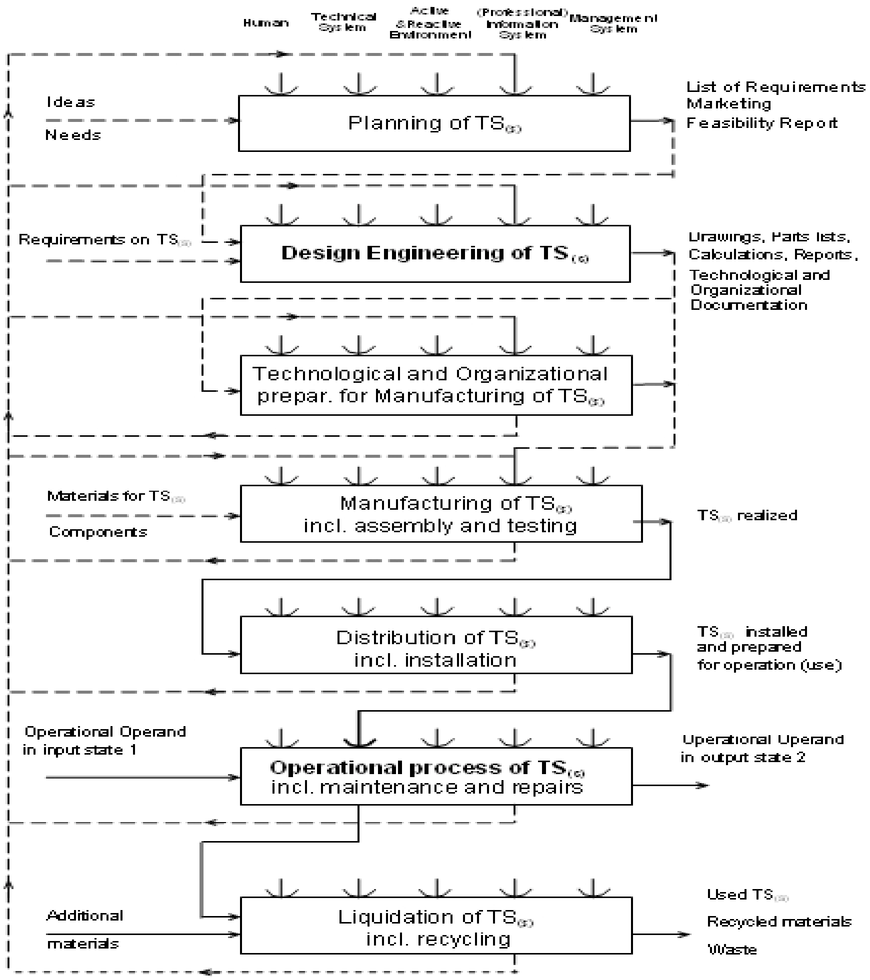

Figure 2: General model of Life Cycle (LC) of the designed Technical Product /System ($TS_{(s)}$) as a 'series' of Transformation Processes (TrfP) and corresponding Transformation Systems (TrfS) [8]

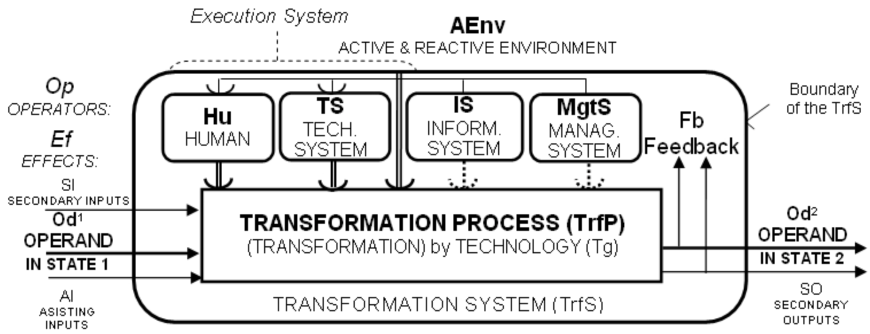

Figure 3: General Model of the Transformation System (TrfS) with Transformation Process (TrfP) [8.]

We can see that all the treated categories of the technical product have obvious analogies in their final specification with their corresponding 'constructional structures', which are necessary for their final implementation/realization, i.e. manufacturing, processing, implementation, and the following distribution, operation, maintenance etc. Thus let us try now to briefly analyse from this viewpoint the three further characteristic and more abstract mass-less 'transformation' structures from the TTS [8, etc.]. They are embedded in the outlined, most concrete constructional structures for the respective generic categories of the technical product. These are 'organ ('function carriers' [9] or mass-less 'solution elements' [15])', 'function (transformation capability)' and 'black box (dummy)' structures, i.e. the respective (hierarchical) elements and ways of their (material, energy, information and spatial) TS internal connections, which can be informally specified as follows:

- organ structure is specified by both TS internal and boundary action sites (i.e. interfaces) and their TS internal connections (see above), which together perform the required internal main transformation and assisting processes and trans-boundary effects;
- function structure is specified by both TS internal and boundary functions (i.e. capabilities) and their TS internal connections, which together perform the required internal main transformation and assisting processes and trans-boundary effects;
- ‘black-box’ (dummy) structure is only specified by TS trans-boundary inputs and outputs

We can see that all these abstract levels taken from TTS can be analogously applied to all the discussed categories of technical products. For example ‘TS processed material organ structure’ can be specified as ‘form-less’ organ performing, with its action sites and their connections (specified by the corresponding TS HW organ structure), the required functions specified in the corresponding function structure, whose trans-boundary inputs and outputs alone specify the corresponding black-box structure. Similarly the ‘TS SW (information) organ structures’ can be specified as ‘function carriers’ and their connections in the form of ‘procedural models/diagrams’, whose trans-boundary inputs and outputs again specify the corresponding black-box structure.

In the case of TS services the task is formally more complex because the designing of a TS service means, in terms of TTS, designing the whole transformation processes (TrfS) (Figure 3) which provides the required services (AW) in the required ‘place’ of the TS LC (Figure 2). In any case it is obvious that it is also in this case principally possible to define all the mentioned structures from the most concrete fully specified ‘constructional structure’ of the TrfS to its most abstract ‘black-box structure’ with its trans-boundary inputs and outputs.

From the viewpoint of the ***Engineering Design Process*** we can now see that this conclusion can lead to a principal possibility of the mutually consistent, stand alone domain specific (see above), design engineering, development and realisation/implementation of the respective generic categories of technical products. This can be principally performed advantageously on the basis of the ‘General Procedural Model of Design Engineering of TS’ [1996], which is theoretically supported by step by step iterative concretisation of the TS structures, beginning with the process structure, through the functional and organ structures to the (rough and full) constructional structures as shown in a simplified form in Figure 4 [7]. This procedure is both fully theoretically supported by iterative concretisation of TS structures, and can ‘communicate’ with all traditional procedural as well as with the ‘best (and even worse) practice’ engineering design strategies [7].

3 DESIGN ENGINEERING OF HETEROGENEOUS TECHNICAL PRODUCTS

Looking at the most usual heterogeneous technical products we can generalize that the ***TS processed materials (FW)*** serve mostly as relatively stand-alone TS and TrfP inputs during the TS LC, and that ***TS services (AW)*** are more or less stand-alone TS LC ‘assisting activities’ (Figures 2 and 3). The FW and AW ‘constructional structures’ are thus not directly embedded/integrated into the TS constructional structure, which allows their relatively separated nevertheless knowledge integrated design engineering as outlined in the previous chapter.

However, very strong and sophisticated interactions arise between ***TS HW*** and ***TS SW***, especially in the case of advanced mechatronic products [15]. When designing such highly internally interacting TS constituents TS HW has firstly to be differentiated into the planned ‘passive’ (controlled) ***basic HW(sub-)system*** and the ‘active’ (controlling) ***sensor, actor and IT HW (sub-)system***. The ‘passive’, basic (sub-)system is principally the ‘core’ goal/purpose technical product whose constructional structure is adopted to be controlled by the complementary ‘active’ (sub-)system.

Considering the roughly outlined procedure of the engineering design process of TS outlined above, we can see that the process and function structures of any designed TS are independent of their future realisation/implementation by the ***basic HW(sub-)system*** or by the ***sensor, actor and IT HW (sub-) system*** (including the relevant SW). The crucial division is made during the transition from the TS function structure to TS organ structure using, for example, the method of morphological matrix (Figure 5).

Here possible organs (see above) are assigned to the respective established TS functions. Thus it is also the right place for ***sensor, actor and IT HW& SW*** organs, to be consistently included in the designed TS organ structure besides the traditional HW (‘pure-’) mechanical, electro-mechanical, hydraulic(-mechanical) or pneumatic(-mechanical) TS organs, which is finalised in the next phase into the final (rough and full) constructional structures.

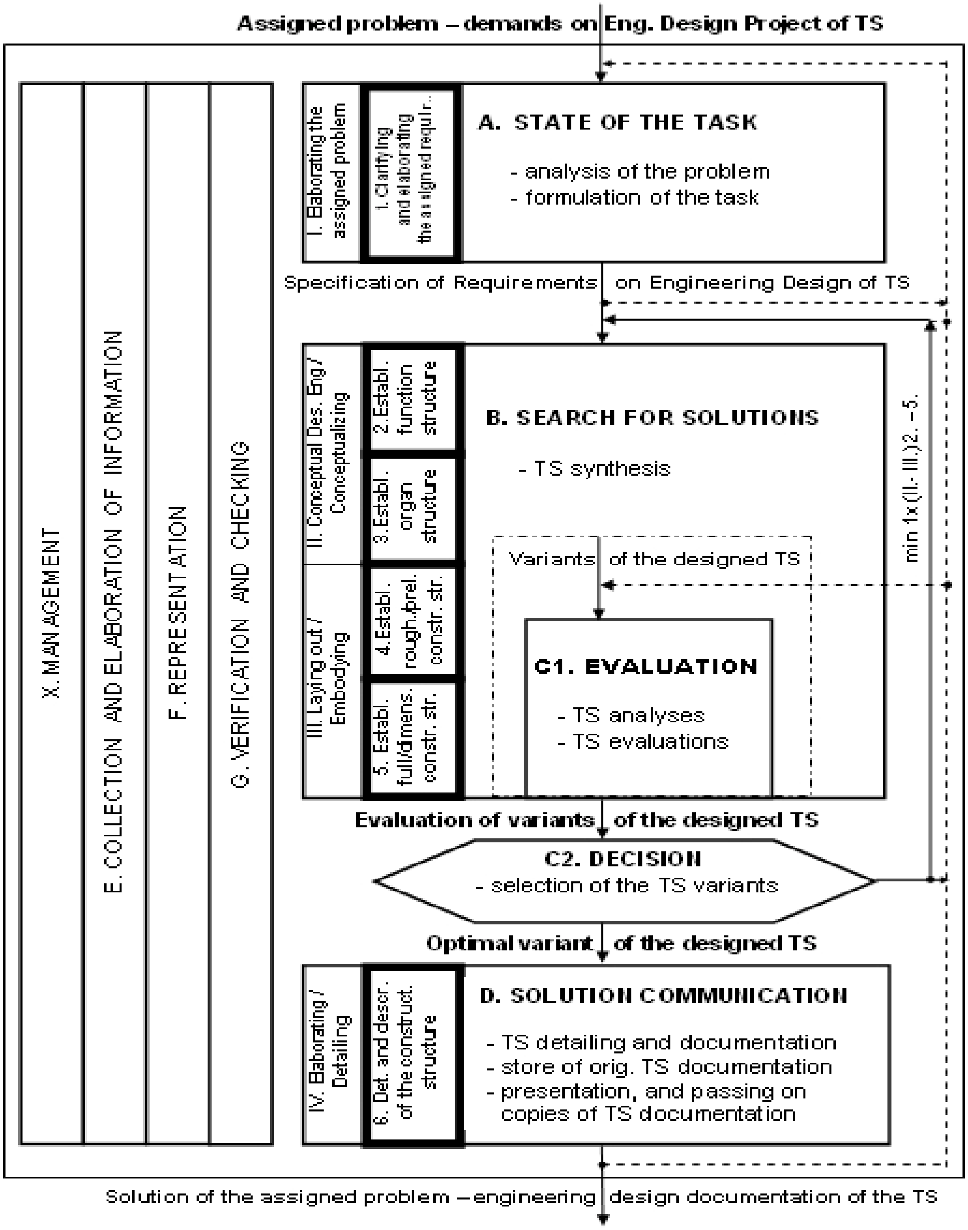

Figure 4: Basic structure of the General Procedural Model of System Design Engineering of TS 1.-6. [9] => [7]

Thus the engineering design process of HW and SW constituents is joint until the stage of the designed TS Function Structure (Figure 4). After that their designs become autonomous using domain specific HW and IT tools (Figure 1). Nevertheless they remain linked by their ‘joint’ TS(s) Function Structure. ‘SW (information) TS modules’ can also be designed, developed (we can even use the identical terms as for ‘HW (tangible/mass) modules’ for these activities) and used in the form of repeatable ‘TS SW Elements’ analogously with ‘TS HW modules’ (traditionally called ‘Machine Elements’). This for example enables the inclusion of such ‘TS SW elements’ as a specific domain of the joint system of ‘Technical Product Elements’.

A series of further analogies enabling similar integrations exist. Of course the use of ‘SW (information) organs’ will probably be restricted mainly to ‘control processes’, but no explicit constraints obviously exist. Of course, ‘SW constructional modules’ must be carried by tangible HW (material) media like microchips, CDs, etc., because SW (information) itself is mass-free, however it cannot exist without mass. These HW media are designed and realised analogously as ‘tangible (object) TS’. SW is stored on them using ROM or RW technologies, based on more or less generally known changes of their TS constructional structures, ‘beginning’ with holes in punched tapes, through changes of the magnetic state of their material of magnetic tapes or discs to micro-imprints made by laser on the surface of a CD, etc.

Functions		Action principles and related Families of Organs or Organs						
		1	2	3	4	5	6	7
1	ENABLE Connection with workpiece	form locking	*mechanical* screw or bolt	wedge	*Friction force locking* pneumatic	hydraulic	magnetic	
2	ENABLE rotational movement	*Rotational guidance* sliding journal bearing	rolling bearings	combined with tilting				
3	ENABLE tilting movement	cylinder	sphere	fulcrum pin	hanger from above			
4	ENABLE vertical movement	straight line guidance	screw thread	linkage	sliding bracket			
5 6 7	LOCK position states	direct by hand	*Form locking* hole and pin	ratchet mechanism	within the guidance – screw thread	*Friction force locking* screw, screw with washer	wedge, brake block	
2.2 3.2 4.2	ENABLE drives – by hand	direct	pair of gear wheels	rack and pinion	*with mechanical advantage* crossed-axis helical gears	worm and wheel gearing	band, rope, chain	lever, eccentric, cam
2.1.1 3.1.1 4.1.1	ENABLE movements regulation	through drive mechanism *mechanical*	through locking (ratchet)	**HW&SW**				
2.1.2 3.1.2 4.1.2	INDICATE position states	reference line+scale	pointer + scale	optical	electronic	mechanical stop	none	**HW&SW**

A.B.C.D

Figure 5 Morphological Matrix with possible Organs related to the established Functions of TS, and with their considered combination – an example

4 CONCLUSION

The outlined analyses and results show that the fundamental models of the generic categories of constituents of the heterogeneous technical products i.e. TS hardware (HW), processed material as formless-ware (FW), software (SW), and services as assistance-ware (AW), including the relevant basic procedural models corresponding to their life cycle (including the engineering design process), are consistent with the core models, which stem from TTS [8].

For example the basic constituents of a mechatronic product i.e. 'passive' TS basic system (which is 'controlled') and 'active' TS sensors, actors and IT processing [15] (which 'control' the TS basic system) serve as HW&SW and HW organ and constructional elements fulfilling the functions established to satisfy the required trans-boundary effects and other properties. TS processed material constituents serve as main, auxiliary or secondary material inputs and outputs of the designed TS and corresponding 'Operational TrfS', and TS services constituents serve to provide e.g. distribution, maintenance, liquidation and other TS Life Cycle processes.

The TS service (AW) constituents can be designed as a corresponding TrfP or complete TrfS, the operand of which is the designed TS [9]. The TS processed materials (FW) are usually included in the design engineering of the designed technical product as its TS (and/or TrfP) inputs.

However, much stronger interrelationships within the elements of heterogeneous technical (and especially mechatronic) products require substantially more interrelated relevant development procedures and changes of the weightings of their basic operations (e.g. increasing importance of simulations and virtual prototyping for early validations of the designed TS behaviour), which are comprehensively described for mechatronic products e.g. in [15].

The presented approach, comprising all four generic categories of products [12] on the basis of TTS [8] can obviously be implemented as integration strategy for the above mentioned Hardware and Software oriented parallel 'Domain-Specific Designs' (i.e. Mechanical Engineering, Electrical Engineering, and Information Technology) in the 'V' Model of Design Development of Mechatronic Products [15]. Furthermore, when the remaining two constituents, i.e. processed materials and services are also included, it can be used for design engineering of heterogeneous technical products in the full [14] context.

The presented concept has already been partially validated in several university engineering design projects successfully undertaken for and evaluated by Czech and foreign industrial partners (Dental, Flabeg, Grammer, Value, Škoda).

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