AEDS 2006 WORKSHOP
27 – 28 October 2006, Pilsen - Czech Republic

TRANSFORMATION SYSTEMS – REVISITED

W. Ernst Eder and Stanislav Hosnedl

Keywords: Transformations, design zones, operands and operators

1. Introduction

A basic model for Engineering Design Science [Hubka 1996] is that of the *transformation system*, see figure 1. The model for an existing transformation system declares:

- **An *operand* (materials, energy, information, and/or living things – M, E, I, L) in state Od1 is transformed into state Od2, using the active and reactive *effects* (in the form of materials, energy and/or information – M, E, I) exerted continuously, intermittently or instantaneously by the *operators* (human systems, technical systems, active and reactive environment, information systems, and management systems, as outputs from their internal processes), by applying a suitable technology Tg (which mediates the exchange of M, E, I between effects and operand), whereby assisting inputs are needed, and secondary inputs and outputs can occur for the operand and for the operators.**

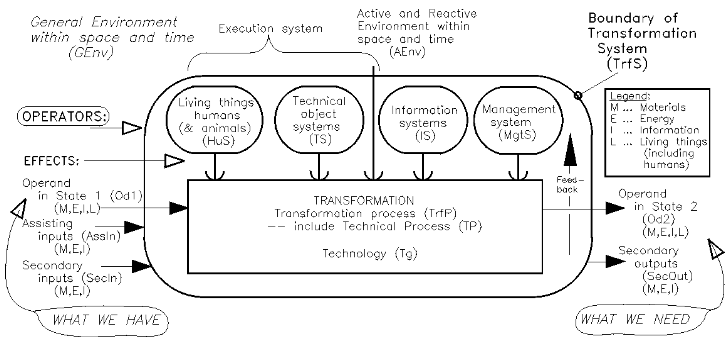

Figure 1. Model of Transformation System

The transformation *process*, TrfP, in which the operand is transformed, and the five *operators*, HuS, TS, AEnv, IS and MgtS, are constituent parts of the transformation *system*, TrfS. All operators interact, see figure 2.

Technical systems (TS) are a sub-grouping of ‘artifacts’, i.e. those that have a substantial engineering content. The term *technical system* is usually understood to mean ‘a tangible technical object (artifact, product) that is capable of performing a task for a purpose’ and is used as the collective term for such objects. The purpose is a technical process (TP). *Machine systems*, as special cases of technical systems, use mainly mechanical modes of action, including fluids and fluidics. Systems increasingly tend to become hybrids, particularly with respect to propelling and controlling, e.g. electro- and computer-mechanical systems, mechatronics, robotics, MEMS (micro-electro-mechanical-systems). The more limited term ‘machine system’ is therefore primarily to be regarded as a collective term for all TS with a mechanical mode of action, mainly products of mechanical engineering.

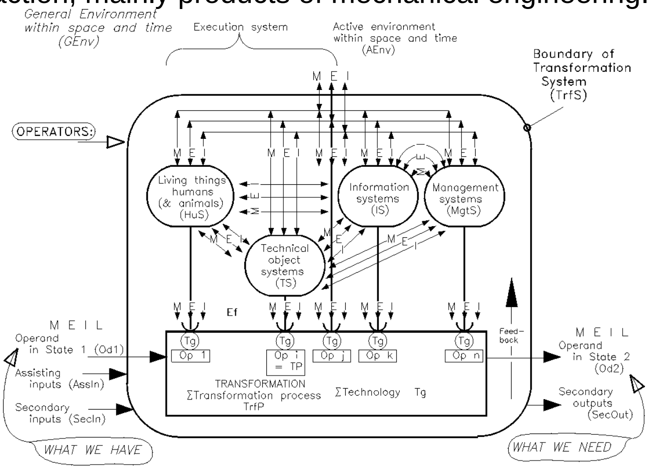

Figure 2. Interaction of Operators

An *effect* is an intended (M, E, I) output of the chain of operator-internal processes, that acts or reacts directly or indirectly through a *technology* to directly transform the operand. The effect delivered by a technical system (TS) is produced by the TS-action chain, its functions, organs and constructional parts, see figure 3. Other outputs exist, i.e. secondary outputs, that can come from the transformation process TrfP, or from any of its operators. For this reason the arrow for secondary outputs in figure 1 starts from the boundary of the transformation *system*, TrfS. ‘Leaking oil from a gear box’ is a secondary output from a TS, ‘heat from losses of energy transmitted by the gear box’ is a secondary output from the transformation process that is performed by the TS ‘gear box’ on the operand ‘rotary energy’.

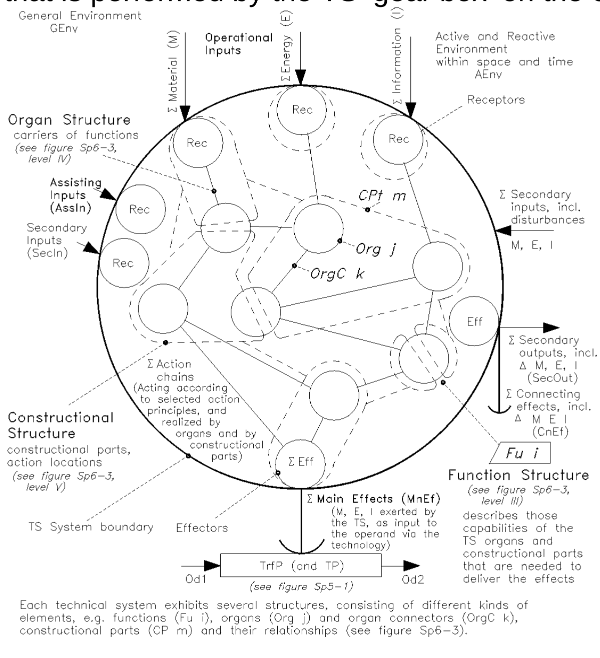

Figure 3. Internal Structures of Technical Systems

The more usual description in the colloquial and general technical language is ‘a (manually operated) universal lathe produces rotationally symmetrical parts by a cutting operation known as turning’. This way of expressing the transformation process ‘manufacturing’, ‘turning’, ignores the necessary active and reactive exerted *effects* (actions) of the human operator – setting the cutting tool, chucking the work-piece, driving the feed motions, etc. – without which a rotational part cannot result. The lathe, by itself, can only hold and rotate a work-piece as operand, the chuck is *active*, it exerts an effect. The lathe can also hold a cutting tool and move it in a plane, the tool is part of the TS and its effect is *reactive*. The *technology* is shear deformation of a small part of the operand to produce a different surface, and chips – and only (for a manually operated lathe) when the human operator provides the necessary force/torque (energy) and regulating motions (actions, output effects). If we want to use all the available capabilities of a lathe to exert effects, we could also wind helical springs – a very different process from cutting, with a modified technology of guiding and bending a wire, and a different tool to accomplish a different transformation within the functional abilities of the lathe (and those of the human operator). This is the main justification for distinguishing the transformation process from its operators.

Action locations may be points, surfaces, volumes, etc., usually on constructional parts of a TS. *Organs* are pairings of action locations on adjacent constructional parts. The trans-boundary action locations (organs) of a universal lathe are the conical point of its (live or dead) center in the tailstock, the chuck (or faceplate, live center and driver) and the cutting edge and faces of the tool – these are the *effectors* of the TS 'lathe' (TS-operator) that act on or react to the work-piece (the operand), i.e. they are capable of performing the holding and cutting actions (effector functions). The guideways between bed and carriage, and between carriage and top-slide are considered in this overall 'window' (see below) to be internal to the structure of the TS 'lathe', their capabilities are described by TS-internal *functions*.

We usually use the word *exerted* or *main effect* to designate an active or reactive output (M,E,I) of a technical system delivered at its effectors. The term *function* is used to designate the capability for performing an internal or trans-boundary (receptor or effector) action. The range and variety of effects that a technical system can deliver are colloquially termed its 'functionality'. A TS is *operational* when it is in a suitable state to perform its TS-internal processes, and is *capable* of producing the needed effects, idependent of an operand.

Effects are *exerted* by the operators, especially the TS (although 'emitted' might be a better verb for radiation). The same effects are *received* by the operand, and converted in form because of the technology,. According to Newton, 'action and reaction are equal and opposite' for force, moment and pressure. An analogy holds for voltage, temperature, and other quantities. Therefore we only need to talk about the exerted effect, and the technology.

It is important to note that the *TS-internal processes* described here are special, because they mostly take place without the direct intervention of the human. This makes the TS-internal processes distinct from the general transformation process, where an operand is topologically 'external to' the TS, and is transformed using a selected technology (based on a technological principle) under the combined action and reaction effects of technical systems, humans and the active and reactive environment (and indirectly by the other operators), with the purpose of realizing a certain more desirable state of the operand.

The goal of designing a TP(s) is to achieve an optimal output state, Od2, of the operand, within an appropriate time and cost. The goal of designing a TS(s) is to create an operational TS. Thinking out of new or revised technical products, *design engineering*, needs to take place in smaller stages of progress, and in smaller sections (parts, assembly groups) of the resulting system. Design problems often need to be sub-divided into smaller 'windows' [Nevala 2005], and the selected alternative solutions re-combined. When a designer dives into detail, e.g. a form-giving zone [Hubka 1992] where forms and sizes of organs are established, he/she also recalls relevant general and professional information, e.g. mental models of the surrounding constructional structure. Nevertheless, the designer comprehends the total problem through a restricted immediate 'window', as a design zone. The boundaries of that window are determined by the immediate design task, the personal knowing and the organizational position of the individual. For the purposes of a design process, we can and should draw an arbitrary boundary around the technical process TP(s), and/or around the technical system TS(s), that is of immediate interest. These boundaries can and will change as design engineering progresses, the 'window' is subject to zooming in and out, and to abstracting and concretizing changes.

The choice of technology, Tg, permits establishing the structure of the technical process, TP(s), the operations and their arrangement, including decision operations that only activate one or other branch of the process structure. The choice of technology also permits establishing the type of effects that must be received by the operands. This then leads on to establishing the requirements that need to be placed on the humans, the technical means and the active environment, i.e. the allocation of tasks to these executing operators, and especially for the effects they must exert. For instance, figure 4 shows how the technological principles of ‘applying lateral force to achieve plastic deformation’ and ‘sliding contact between surfaces’ are applied to the technology of ‘pulling wire through a tapered narrowing opening to reduce its diameter’.

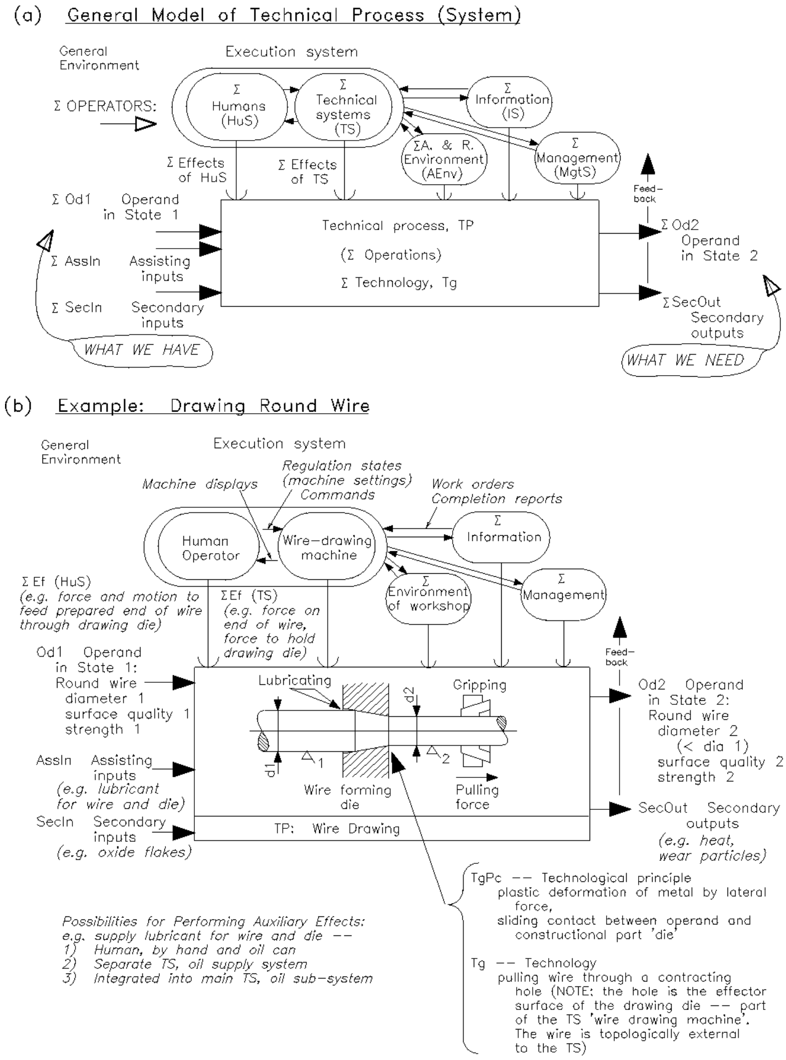

Figure 4. Example: Wire Drawing

2. Examples

Some examples should illustrate the concepts outlined above, and show their usefulness for design engineering.

2.1 Operator *vs* operand

Both of these are relative terms, they depend on the point of view, the ‘window’, adopted by the observer. We need to clarify the boundaries of the TP(s) and the TS(s). The *operand* of the transformation process is being changed in various *operations*. The operand must generally be regarded as existing and being changed (topologically) ‘external to’ the operators, thus also ‘external to’ the technical system. Defining the operand (and therefore defining the boundary of the technical system under consideration) is therefore an important part of the design process.

A) A taxi driver is normally operator and operand, whilst actively steering the vehicle, and may occasionally be only operand, being transported by the vehicle when he falls asleep. A taxi driver is not part of the TS ‘vehicle’, he is topologically (placed) external to the vehicle, even though he is surrounded by the vehicle – and he can get in and out. He actively and reactively causes the technology of motion to take place, and is therefore operator. On the other hand, we cannot cover all possible circumstances, not even mathematics can claim to be so complete and non-contradictory.
B) Consider an ‘automotive wheel’. The rim, the tire, the valve, and air are the operands, Od1, at the input to the ‘black box‘ transformation process ‘mounting a tire’. Individual operations are: Op1: ‘fix the rim’, Op2: ‘insert the valve’, Op3: ‘mount the tire’, Op4: ‘inflate the tire’, Op5: ‘release the operational wheel’.
For Op1: TSa is ‘tire mounting machine’, Od1a is ‘rim free’, Od2a is ‘rim fixed to TSa’, Tga is ‘clamping’.
For Op2: TSb is ‘tire mounting machine with rim’, Od1b is ‘valve free’, Od2b is ‘valve inserted’, Tgb is ‘valve pulling’.
For Op3: TSc is ‘tire mounting machine with rim and valve’, Od1c is ‘tire free’, Od2c is ‘tire mounted’, Tgc is ‘rotational snapping of tire bead over rim’, AssIn is ‘tire lubricant’.
For Op4: TSd is ‘tire mounting machine with rim, valve and tire’, Od1d is ‘air at normal pressure’, Od2d is ‘air compressed in tire/rim/valve assembly’, Tgd is ‘pumping and guiding through valve’.
For Op5: TSa is ‘tire mounting machine’, Od1e is ‘operational wheel fixed’, Od2e is ‘operational wheel free’, Tge is ‘unclamping’.
It is only when the operational wheel is finally mounted on the axle of a car that the car, TSf, can be operational, and the effects of ‘transmitting force to the ground’ can be realized – the wheel is then internal to the boundary of the TSf.
C) In figure 4, the separable drawing die of the operational TS ‘wire drawing machine’ must be considered internal to the TS, the inner conical face of the die is the effector that will directly contact the wire and cause its transformation in diameter and other properties.

2.2 Technology

A) A water jet is a useful TS-output, its *effect* as carrier of kinetic energy and mass with erosive power, the *technology*, can be applied for cutting metal or rock, the *transformation* operation on the operand – the active end of the water jet is regarded as part of the TS under consideration in this ‘window‘.
B) A mechanical pencil (a technical system) can be used to transform the appearance of a piece of paper by enabling the transfer of graphite from the pencil lead to the paper. The form (shape) of these marks may represent information for the human. The operand of this transformation process is blank sheet of paper, and the intention and meaning (Od1) of the symbols (marks) to be created (Od2). The operators are (1) the human intending and acting to make these marks, e.g. when a human guides the tip of the lead to and across the paper, (2) the mechanical pencil with its ‘consumable’ lead, (3) an environment, (4) an information system, and (5) a management system. The technology is ‘transfer of graphite’, ‘using friction to rub graphite from the lead, and deposit it on the paper’. The TP is ‘marking the paper’. Consequently, a TP can be extracted from a TrfP by focusing mainly on those operations which involve an existing or assumed operation of the TS – its operational process fulfills the real or potential TP – but does not preclude adding other operations if desired.
C) The technology of hardening a piece of steel prescribes an effect of transferring heat to the item (the operand) to achieve a specified temperature, then rapidly transferring heat from the item, cooling and quenching it, to a lower temperature, and usually re-heating it to temper the steel, to reduce its hardness from the maximum ‘glass-hard’ state, and restore some of its ductility, followed by slow cooling to room temperature. The technology of radiant heating requires a radiation source, e.g. the sun or an electric heating element, and a direct line-of-sight to the operand; the radiating energy is considered as part of the acting TS, and is converted at the operand interface to heat.

2.3 Operational

A) A venturi is an *operational* TS even without moving mechanical parts, it is 'capable of guiding a fluid (the operand if it is present) to increase its velocity and then reduce it, and consequently to reduce its effective pressure and then increase it, at constant mass flow rate', whether any *moving* fluid is present or not.

B) A spark-ignition internal combustion engine, TSA, is *operational*, it can be turned over (the crankshaft rotated) by applying a voltage and current input to the starter motor, even with no fuel present. The engine will then pump air from its intake air filter into the exhaust pipe. For the experiments, the engine is mounted and attached to a dynamometer test stand, TSB.

Experiment (B1), the spark-ignition internal combustion engine TSA is the operand (OdA), the test stand TSB is the operator. TSB is operational whether TSA is present or not. TSB can exert effects of rotational motion and torque (as reaction) onto the clutch of TSA, acting as receptor for the spark-ignition internal combustion engine, to run a 'motoring test' to measure the TSA-internal friction resistance. TSA will pump clean air.

Experiment (B2), the spark-ignition internal combustion engine TSA is now the operator. It can again accept voltage and current to turn the crankshaft. An appropriate throttle position is delivered as input to the TSA. It can then also accept the operand in state OdA1 of fresh air plus gasoline fuel, in an appropriate mixture (M, E) including the input information (I) about the chemical composition. The operand enters the cylinders and is compressed (raising its temperature and pressure) – it is still topologically external to the TSA. The TS-technology delivers a spark across the spark-plug gap to initiate an operand-internal chemical reaction known as combustion. The burned exhaust gases are delivered into the exhaust pipe, as secondary outputs carrying M, E, I. Some of the heat is extracted to cool the engine, and is dumped through the radiator to the environment. The TSA reacts the cylinder pressure, and with piston motion extracts some of the resulting heat energy into mechanical translational energy, the useful OdA2. This translational energy is passed eventually to the clutch as rotational energy, external to each constructional part in the action chain using the constructional structure and the organ structure. Here the TSA again acts as operator of the test stand, TSB, and its *operational* process, which measures the output power and rotational speed, and various other quantities.

2.3 Window change

A) The change of window, and change of TS-boundary, may be demonstrated on a dry-powder fire-extinguisher. View (a), if the TrfP of 'extinguishing a fire' is the point of interest, Od1a is 'material burning', Od2a is 'material not burning', the TS boundary includes the jet of dry powder emitted from the extinguisher nozzle, the jet acts on the operand to extinguish the fire by cooling and excluding oxygen.

The next narrower viewing 'window', view (b) would consider the TrfP 'emit a jet of dry powder', independent of any fire, a view that would be needed for tests on the extinguisher itself. Od1b is 'powder under pressure in container', Od2b is 'powder distributed over an area', the TS-boundary is now the container for dry powder with its nozzle. Auxiliary processes are now needed of filling dry powder into the container, pressurizing the contents, retaining and releasing the pressure, and distributing the powder through the nozzle.

B) A water jet is capable of cutting a stone (material as operand OdA) by the effect of kinetic energy and contact with a material surface (the technology TgA), if the stone is present. The water jet in this operational view is an integral part of the TSA. If we now 'zoom in' to a more detailed view, that water jet fulfills a TS-internal function of the TSA 'form a high-speed water jet' – whether the stone is present or not. Using the function of TSA as the transformation process of TSB, the input water to the process (if present) is now Od1B, and the TSB must exert its effects to compress and deliver the water in a high-speed jet (Od2B), using the appropriate technology TgB of 'sucking, transporting, pressurizing, shape-forming'.

C) The food and other things stored in a freezer (TSa) are the *operand*, OdA, and are not part of the freezer, they are 'external to' the freezer, even though they are completely surrounded. The freezer will still operate without the stored items. From this point of view, the operational technical system ‘TSa freezer’ delivers the effect of ‘removing heat energy from the operand space’, but only when it is connected (and switched on) to an electric power supply, one of its inputs.

A different point of view arises for the engineering designers (probably in another organization) who are responsible for designing a refrigeration module, TSb, e.g. for the freezer, TSa. This TSb ‘refrigeration module’ acts as both an organ and a constructional part, and fulfills a function for the technical system ‘freezer’, TSa. For this engineering designer, the liquid/gaseous refrigerant is the *operand*, OdB, even though it is completely contained by parts of the technical system ‘refrigeration module’. The technical system, TSb, will operate even if it has no refrigerant, i.e. rotate the compressor, but not transport heat energy. The technical system ‘refrigeration module’, TSb, consists of the compressor, throttle valve, two heat exchangers, pipes, fittings, electric motor and other parts, and exerts its various *effects* on the refrigerant (operand, OdB) to compress, cool, expand and heat it – the operations in the technical process ‘pump heat’.

Yet another viewpoint arises for the engineering designers (again probably in another organization) who are responsible for designing the electric motor. This electric motor, TSc, acts as both an organ and a constructional part, and fulfills a function for the technical system ‘refrigeration module’, TSb. The operand for the electric motor, OdC, is the compressor, the electrical energy input to the motor is to be processed from electrical to rotational-mechanical, and the torque and rotational speed is the effect that changes the compressor.

D) The terms ‘function’ and ‘technical process’ applied to a formulation depend on the immediate point of view. Consider a *hierarchy of ‘Watching TV’*:

The most complex level of interest occurs during accepting, setting up, and preparing for operation. The *operand* is the TV-set itself in total with all its peripherals. The main operator is the HuS at home, the TS is the power supply outlet on the wall of the room, the AEnv. The *transformation process* of the TV-set as operand is shown in figure 5, part A, and results in a watchable TV.

At the second level the ‘TV is operating, whether watched or not’ (Ops 1.7-1.12 and 1.14 in figure 5, part A). If there is no signal applied to the TS receptor (i.e. topologically ‘external to’ the TS), the output of the TV-set (now regarded as the TS for this next more detailed level) will be only ‘snow’ on the picture tube, and ‘hiss’ from the loudspeaker, i.e. the TV-set will still be operational. All operating inputs, outputs and TS-internal processes (functions) can now be analyzed and established for each of these operations. For Op 1.9 as the TP, the consequent *functions* required of the TS that will deliver the necessary effects are shown in figure 5, part B.

Each of these functions (or groups of functions) can now act as source for the TP for the next more detailed level.

At the third level consider Fu2.29 now as the TP ‘Op2.29 amplify sound signal’. The operating TS for this level is an operational amplifier on a circuit board physically inside the casing of the TV-set, as an integrated circuit ‘component’ viewed as a constructional part. The operational amplifier is typically connected to a ‘supply voltage’ and a ‘bias voltage’ when the TV-set is operational (i.e. switched on), whether there is a signal or not. By applying a small modulated sound signal (Od1) overlaid (i.e. topologically ‘external to’ the TS ‘operational amplifier’) on the ‘bias voltage’, a much larger variation (Od2) of the ‘supply voltage’ can be detected, isolated, and used to drive the loudspeaker. If the variation of ‘bias voltage’ is too large, the output variation of ‘supply voltage’ will be a distorted replica of the input.

3. Closure

In every case, i.e. at every level of abstraction, it is important to recognize the *operand* for the TP, and the transformation that this operand experiences. From this, the tasks of the *operators* can be established, i.e. the *effects* that the operators, and especially the TS at that level, should deliver. With the available inputs to the TS, its (TS-internal) *functions* can be established. Each of these functions (or groupings of functions – capabilities for action) can then act as definition for the TP for the next more detailed level of complexity, until all the constructional parts are established.

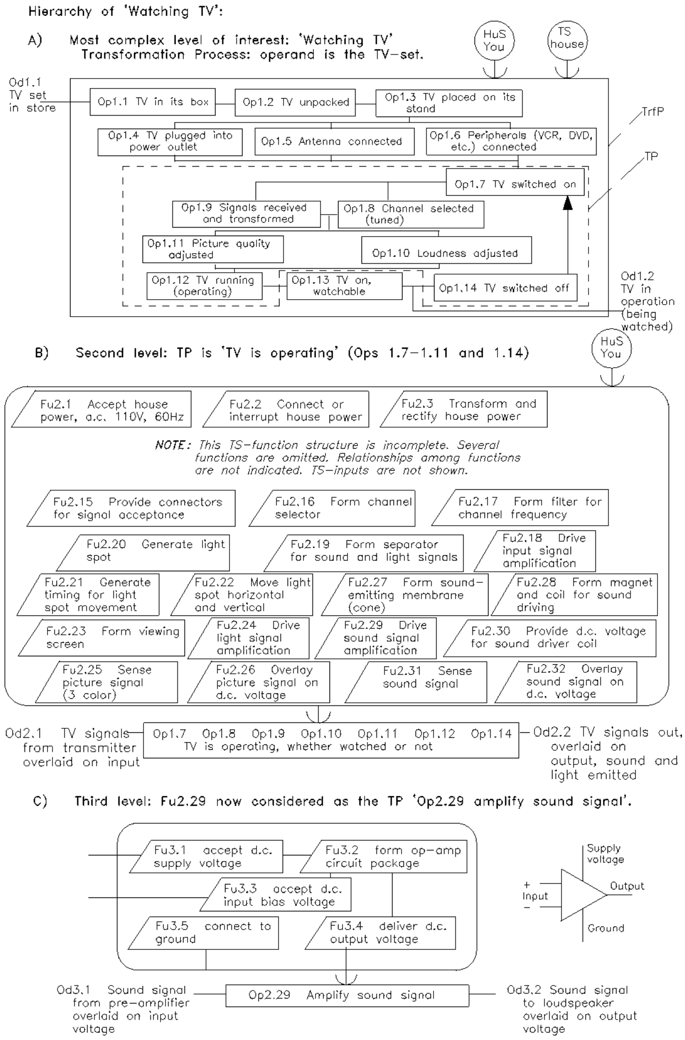

Figure 5. Hierarchy of 'Watching TV'

References

Hubka, V., and W.E. Eder (1992) ***Engineering Design****, Zürich: Heurista (2nd edition of Hubka, V. (1982)* ***Principles of Engineering Design****, London: Butterworth Scientific (Translated and edited by Eder, W.E.,), reprint by Zürich: Heurista, 1987, translated and edited by W.E. Eder from Hubka, V. (1980)* ***WDK 1 – Allgemeines Vorgehensmodell des Konstruierens*** *(General Procedural Model of Designing), Zürich, Heurista*

Hubka, V., and Eder, W.E. (1996) ***Design Science: Introduction to the Needs, Scope and Organization of Engineering Design Knowledge****, London: Springer-Verlag, http://deseng.ryerson.ca/DesignScience/ ; completely revised edition of Hubka, V., and Eder, W.E. (1992)* ***Einführung in die Konstruktionswissenschaft*** *(Introduction to Design Science), Berlin, Springer-Verlag*

Nevala, K. (2005) ***Content-based Design Engineering Thinking****, Academic Dissertation, University of Jyväskalä, Finland, Jyväskalä: University Printing House. http://cc.oulu.fi/~nevala*

W. Ernst Eder, Professor Emeritus, Dr.h.c.
Royal Military College of Canada
107 Rideau Street, Kingston, Ontario, Canada K7K 7B2
x-1-613-547-5872, eder-e@rmc.ca