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RELATIONSHIPS AMONG TS-PROPERTIES, TS-BEHAVIORS AND REQUIREMENTS

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1. Introduction

One of the key features of Engineering Design Science [Hubka 1996, Eder 2008] is the theory of properties. Every transformation process, and every operator of a transformation process possesses properties, whether they have been designed or not. The theory should lay out a general, logical and complete scheme of classification of properties that is valid for all technical systems. This theory must then be adapted for each TS-'sort', and probably for each organization involved with that TS-'sort' [Hubka 1996, Eder 2008, Weber 2007].
Quoting Klaus [1965]: *'Both method and theory emerge from the phenomenon of the subject'.* Figure 1 indicates that close relationships should exist between the subject under consideration (its nature as a concept, product, artifact or process), the basic theory (formal or informal, recorded or in a human mind), and the recommended method. The theory should describe and provide a foundation for the behavior of the (natural or artificial, tangible or process) object, i.e. it should answer the questions of 'why,' 'when,' 'where,' 'how' (with what means), 'who' (for whom and by whom), with adequate and sufficient precision.

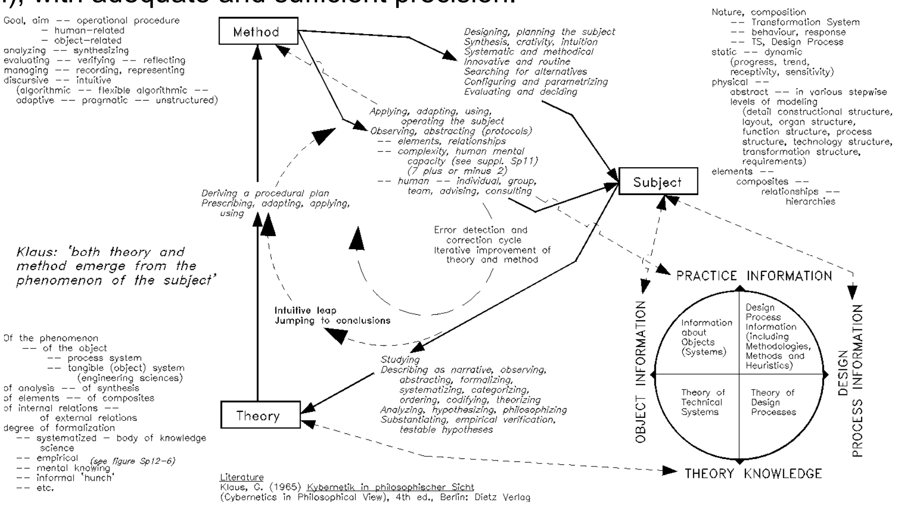

Figure 1. Relationships Among Subject, Theory and Method

The theory should also support the utilized methods, i.e. allow development of answers to the questions of 'how' (procedure), 'to what' (subject), both for using and/or operating the subject, and for designing the subject. The method should also be sufficiently well adapted to the subject, its 'what' (existence), and 'for what' (its anticipated and actual purpose). These three phenomena of theory, method and subject are of equivalent status to each other.
One implication from figure 1 is that if we know a theory of the subject, we should be able to derive a non-compulsory prescription of a method. Using the convention suggested by Koen [2003]: a method is a prescription for anticipated future action, for which it is heuristically imperative that you adapt it flexibly to your current (ever changing) situation, where the underscore under the second letter of a word indicates its heuristic nature – and nearly all words in this paper should have their second letters underscored. Every practice (as subject) can benefit from a well-formulated theory to explain it in generalized terms. Then, the triad of 'theory – subject – method' can help towards using and/or designing the subject.

2. Transformation System

A basic model of Engineering Design Science [Hubka 1996, Eder 2008] is that of the transformation system and its constituents, see figure 2. The model 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* (consisting 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.

The transformation system consists of a transformation process, the service that the TS is expected to deliver, and its operators – it is a product-service system, compare [Müller 2007].

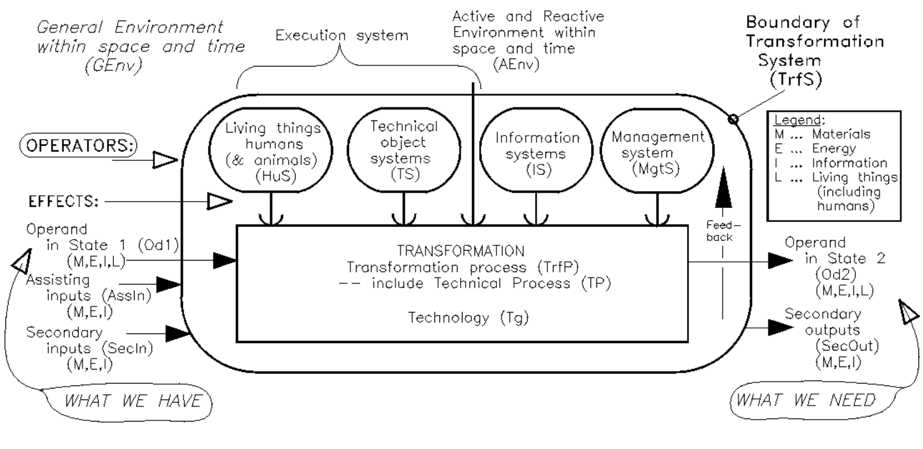

Figure 2. General Model of a Transformation System

For any typical technical system TS(s) as subject of our interest, the life cycle consists of a sequence of transformation processes, each driven by its own operators, as shown in figure 3. This is the minimum number of life-cycle phases that provides complete coverage, and is as general as possible. Each of these typical life-cycle phases is usually composed of many transformations, but these can no longer be specified in the general way demanded by Engineering Design Science – each TS-'sort' has its own specific variants.
In the first three of these typical life-cycle phases, LC1 – LC3, the TS(s) exists only as information [Eder 2006a]. A tangible form of the TS(s) exists in the other phases, LC4 – LC7,

together with the information content of that particular tangible form as designed and manufactured.

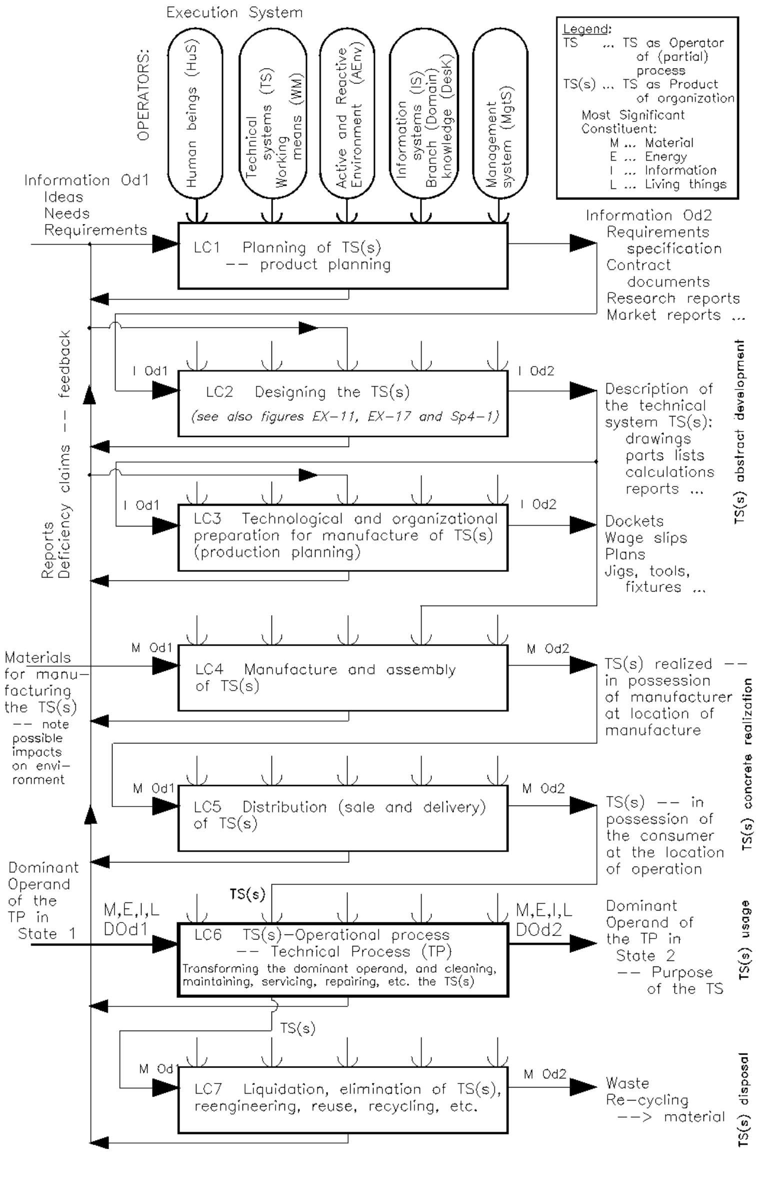

Figure 3. Life Cycle of Technical Systems

3. Properties – Theory of Properties

The theory of properties has been under continuous development within Engineering Design Science [Hubka 1996, Eder 2008]. A first listing of TS-properties appears in [Hubka 1973], and the concept has been progressively refined in various other books by that author. For instance, in [Hubka 1984 and 1988] the external properties that anyone can observe are differentiated from the internal properties that the engineering designers control and use. The latest version [Hosnedl 2004, Eder 2006a and 2008] shows a theory-based arrangement.

According to Smith [2005], see figure 4:

(1) Properties *Define* Entities: properties are behavioural characteristics that an entity possesses. Since only this behaviour is used, properties completely define entities.

(2) Relationships *Require* Properties: for relationships to make use of behaviour, the entity must have that behavioural characteristic or property.

(3) Relationships *Constrain* Entities: relationships in some way constrain the use of entities since each entity must maintain certain relationships with other entities. It is through relationships that the use of entities is bounded.

In our case, the entities are transformation processes, or technical systems, see figure 2.

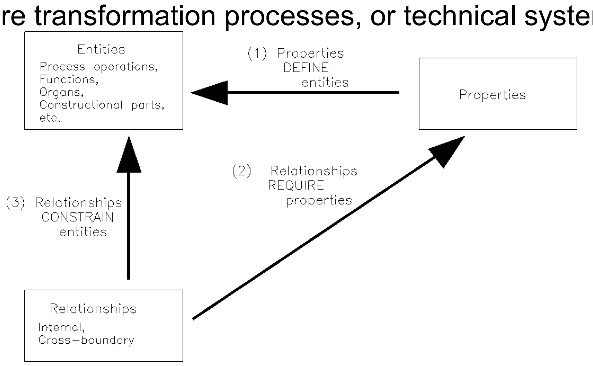

Figure 4. Group Entities and Links for an Existing System

Classes of properties for a *transformation process* (TrfP), see figure 2, consist of (a) the properties of the operand, in state Od1, Od2, and in each intermediate state, (b) the properties of any assisting and secondary inputs, (c) the properties of secondary outputs, (d) the types of transformations or operations that can be performed on an operand, and (e) the active and reactive effects exerted by the operators that cause the transformation of the operand by means of an applied technology.

The primary class of properties of *technical systems* should relate to the TS(s) as operator of its operational process (LC6), i.e its usage for its intended purpose – we will label this as class Pr1. Further classes of TS-properties are needed for the other life-cycle processes where a tangible TS(s) exists – classes Pr2 – Pr4. Figure 5 shows the derivation of classes of TS-properties to provide a complete coverage of all external properties, resulting in a matrix of considerations for operators of those life-cycle processes – classes Pr5 – Pr9.

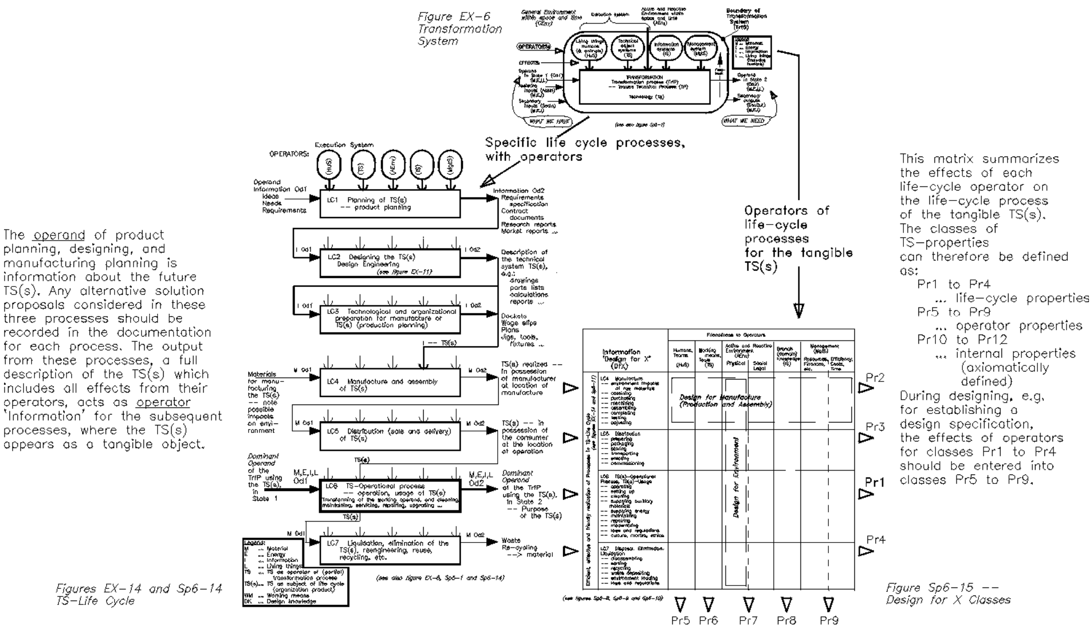

Figure 5. Derivation of Classes of Properties of Technical Systems

In addition, three axiomatic classes (Pr10, Pr11 and Pr12) of internal properties (also called design properties) are needed. These are the properties that an engineering designer has under his/her direct control, and with which he/she should realize the required external properties of the future TS(s). The class of internal properties is sub-divided into Pr10 design characteristics, Pr11 general design properties, and Pr12 elemental design properties. The design characteristics and the elemental design properties are causally responsible for the manifestations and values of the general design properties. The elemental design properties include the elements and relationships among them, i.e. the structures of technical systems at various levels of abstraction: function structure, organ structure and constructional structure. It appears therefore that the TS-structures are a sub-set of the TS-properties.
These twelve classes constitute a minimum set to provide complete coverage, and to be as general as possible, see Table 1.

Table 1. Primary Classes of TS-Properties

Life Cycle Related Properties – External Properties 1
Pr1 Purpose properties
Pr2 Manufacturing properties, planning and preparation – realization properties, manufacture, assembly, adjustment, packaging, etc.
Pr3 Distribution properties, maintenance and service organization, warranty, consulting
Pr4 Liquidation properties
Operator Related Properties – External Properties 2
Pr5 Human factors properties _ ergonomics, esthetics, psychology, cultural acceptability
Pr6 Properties of factors of other TS (in their operational process, TP)
Pr7 Environment factors properties
Pr8 Information system factors properties – including law and societal conformity, cultural, political, and economic considerations, information availability, etc.
Pr9 Management factors properties
Engineering Design Properties – Internal Properties
Pr10 Engineering design characteristics
Pr11 General engineering design properties
Pr12 Elemental engineering design properties

Sub-classes are needed or useful in several of these TS-property classes to clarify the context of the life cycle, its operators, and especially its active and reactive environment, e.g. management. Additional guidance on TS-properties may be obtained by listing complete sets of secondary property classes, see Table 2. The secondary classes are theoretically founded for primary classes Pr1–Pr6, and are based on more pragmatic considerations for the primary classes Pr–Pr9.

Table 2. Primary and Secondary Classes of TS-Properties

Life Cycle Related Properties – External Properties 1
Pr1 Purpose properties
Pr1A Function properties – behavior – effects properties
Pr1B Functionally determined properties – parameters, properties conditional on functioning (operating)

Pr1C Operational properties
Pr2 Manufacturing properties, planning and preparation – realization properties, manufacture, assembly, adjustment, packaging, etc.
Pr3 Distribution properties, maintenance and service organization, warranty, consulting
Pr4 Liquidation properties

Operator Related Properties – External Properties 2

Pr5 Human factors properties _ ergonomics, esthetics, psychology, cultural acceptability
Pr5A In manufacturing, LC4
Pr5B In distribution, LC5
Pr5C In operation, LC6
Pr5D In liquidation, LC7
Pr6 Properties of factors of other TS (in their operational process, TP)
Pr6A In manufacturing, LC4
Pr6B In distribution, LC5
Pr6C In operation, LC6
Pr6D In liquidation, LC7
Pr7 Environment factors properties
Pr7A Social, cultural, geographic, political and other societal factors
Pr7B Materials, energy and information
– TP/TS inputs – effects of and on environment
– TS_material – effects of and on environment
– TP/TS secondary outputs and TS disposal
Pr8 Information system factors properties – including law and societal conformity, cultural, political, and economic considerations, information availability, etc.
Pr8A Scientific information
Pr8B Technological information
Pr8C Societal information
Pr8D Legal information
Pr8E Cultural information
Pr8F Other information
Pr9 Management factors properties
Pr9A Management planning – product range
Pr9B Management of design process
Pr9C Design documentation – design report, version control
Pr9D Situation – management climate, personnel relationships, etc.
Pr9E Quality system – quality of design, quality control, quality assurance
Pr9F Information properties – licensing, intellectual property, etc.
Pr9G Economic properties – costs, pricing, returns, financing, etc.
Pr9H Time properties – delivery, planning, process durations, repair, maintenance, etc.
Pr9J Tangible resources – availability, accessibility, etc.
Pr9K Organization – goals, personnel, etc.
Pr9L Supply chain properties – availability, delivery time, reputation, reliability, etc.
Pr9M Other management aspects

Engineering Design Properties – Internal Properties

Pr10 Engineering design characteristics – modes of action, technologies, form-giving principles, etc.

Pr11 General engineering design properties – strength, stiffness, etc. – related to the engineering sciences

Pr12 Elemental engineering design properties – Structure, elements, TS-internal and cross-boundary functions, organs, constructional parts – forms, dimensions, materials, types of manufacturing, tolerances, surface finishes, etc.

All properties of all transformation processes and tangible technical system can be classified into the above scheme without remainder. Each property may appear in different manifestations, many properties have values, most of which also have scales and units of measurement.

4. TS-Behavior

Listed among the secondary properties in sub-class Pr1A is *behavior*. This is defined as the succession of states that a TS assumes in response to its stimuli. The states in turn are defined by the mixture of properties, their manifestation and values at any one time.

The states of properties exist and change under various operating states, the 'duty cycle' of the TS: (a) at rest, no operation; (b) during start-up; (c) during normal operation – idling, full-power and part-load, overload, etc., for self-acting operation (automatic), or running and ready to be operated by another operator, e.g. human or another TS; (d) during shut-down, ending an operational state and returning to 'at rest' conditions; (e) in fault conditions – (e1) internal faults – overload, safe trip-out, breakage or equivalent, and (e2) external faults – damage, wrecking, etc.; (f) during maintenance, repair, testing, etc.; (g) at 'life ended'; (h) any other states.

The technical system, TS(s), as operator of its technical process, TP (a constituent part of the transformation process, TrfP, see figure 2), may (A) act alone, or (B) act in cooperation with other operators (especially human and information systems), or (C) be operated by a human system, quasi as an extension of the human's capabilities. The transformation can only be achieved if the TS is operational (capable of operating or being operated) and is actually delivering the desired effects, via the technology, to the operand of the TrfP. The TS is operational if it is capable of fulfilling its internal and cross-boundary functions. We strictly distinguish between the TS-functions (internal and cross-boundary) and the operations in the transformation process [Eder 2006b], in contrast to Pahl [2007] where the TrfP operations are also called 'functions'.

4. Requirements

We also acknowledge a difference between 'determining' and 'establishing' a property. Once a tangible TP(s) and/or TS(s) exists, even if only as an incomplete collection of constructional parts, various properties can be *determined* by measuring, simulating or assessing. Before a tangible TP(s) and/or TS(s) exists, we need to *establish* the needed internal properties, to predict in advance what manifestations and values may be possible and useful, how to achieve them by the internal design properties – we need to *design* the TP(s) and/or TS(s).

According to Smith [2005]:

(4) Properties *Become* Requirements: groups can be combined into hierarchies and a property in a parent group is converted into a requirement in a child group.

(5) Relationships *Resolve* Requirements: relationships make use of the entity behaviour to resolve requirements, such that each requirement is assigned to at least one relationship, and each relationship is assigned to at least one requirement.

(6) Properties *Maintain* Relationships to *Resolve* Requirements: properties indirectly resolve requirements by maintaining the relationships that directly resolve requirements. Thus the property maintains a relationship such that the relationship can resolve a requirement. To determine what properties an entity must have, one must combine its relationships with their requirements.

Together with the statements from Smith [2005] in figure 4, figure 6 shows the complete set of links among these concepts.

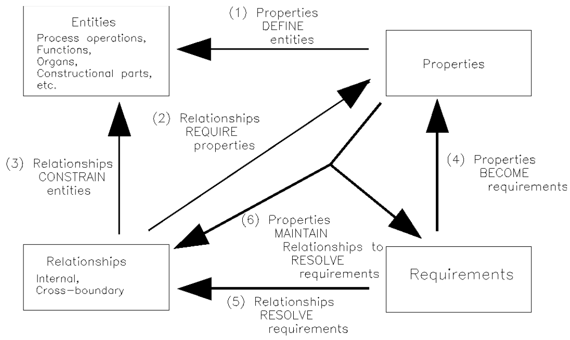

Figure 6. Group Entities and Links for a Required New Technical System

Technical systems are always created and manufactured for a specific purpose. A need exists, or a market opportunity is recognized, and is usually expressed as a set of requirements for a suitable selection of external properties – from the viewpoint of the customer and/or user of the future TS.

From the viewpoint of Engineering Design Science [Hubka 1996, Eder 2008], this given set of requirements is not sufficient for design engineering – the design specification that should be developed for a future TP/TS (Product-Service System [Müller 2007]) should be more complete. The design specification should include target values and/or limiting values (maxima, minima, or both as a tolerance range) of relevant properties.

The scheme of primary and secondary properties, especially classes Pr1–Pr9, is a good basis for proposing a list of requirements – but even this is not sufficient. Engineering designers should also be aware of the policies, requirements, facilities and constraints of the organization within which they design 'their' TP and TS. In the first three of the typical life-cycle phases in figure 3, LC1 – LC3, the TS(s) exists only as information [Eder 2006a] – and it is particularly the policies, requirements, facilities and constraints of these three life-cycle phases that must be covered.

Policies typically include such statements as (deliberately fictitious names are used for these examples): "our car doors should close with the distinctive sound of a Mercrolet". Facilities would typically include "use of SolidCAD graphic, analysis and manufacturing software". Constraints will normally include statements about cost limitations. In this way, the design specification will cover all life-cycle phases.

During the life-cycle phases LC1–LC3, especially during design engineering, various alternative solutions will normally be considered, and various analyses, simulations and experiments will be performed. The resulting information should be held in the files of the designing organization, preferably in a comprehensive design report. The only information about the future product that will be released to manufacturing will be the final decision about the chosen alternative, the one product to be made and offered on the market. This TP(s) and/or TS(s) is expected with reasonable confidence to comply with all requirements and constraints, whether stated in the design specification or not, relevant to all life-cycle phases, i.e. to exist *within* the given limits. Once the TP(s) and/or TS(s) is in a tangible state, it is difficult or impossible to conclude 'backwards' to the imposed requirements and/or constraints.

4. An Example

Consider an organ for an internal combustion engine, a connection of a coolant hose to a cylinder head or block, and to the radiator.

Requirements (input to LC2) include:
– must be able to make a good seal to a standard engine pipe end, cold (- 40□C) to hot (100□C) and at over-pressure up to 100 kPa;
– must be able to withstand chemical actions of coolant for at least 3 years;
– must allow enough space for assembly (tools and body positions);
– organization-internal constraint: use SolidCAD.
Alternatives considered are recorded.
As designed (output of LC2/LC3, input to LC4):
– pipe end O.D. 30 mm diameter (h9 tolerance), 25 mm long, end ridge to O.D. 31 mm (h9) with 1 mm radius;
– hose end square to ± 1□, I.D. 30 mm (H11), Shore hardness .....;
– confident that it will fulfill all requirements and constraints LC1-LC7.
As manufactured (output of LC4):
– pipe end O.D. mean 30.007 mm, std. dev. 0.002 from 65 samples;
– conforms to drawings.
In service (during LC6):
– mean time to failure 4 years 3 months, std. dev. 5 months, from 17 reports from repair workshops.
Feedback to design and organization management:
– requirements fulfilled by manufactured TS(s), may need to be improved for next generation.

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