Estimation of environmental effects in early product development

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Abstract: Thinking ‘green’ early in product development process is of outmost importance while developing environmentally advanced products and solutions. Current Ecodesign practice is focused on product’s life cycle analysis, creating options for improvement of environmental effects of artefacts. The paper examines the potential of estimating environmental effects in conceptual design stage by assessing product’s working principles. Working principles are used to elaborate how the product fulfils its function, supply and facilitate effects to perform the desired transformation of energy, material and information. Working principles can be correlated with principle solutions recognized as being suitable for delivering desired functions and effects, where effects are defined by physical laws. The research is based on the assumption that when principle solutions for delivering required effects and product’s function are established, environmental impacts are indirectly implied and could be managed in the early stages of product development. Building the structure of future product, creating relationships between desired effects, principle solutions and chain of required internal transformations, secondary or side effects (outputs) towards active or immediate environment can be anticipated. Following the premise, analysis of working principles and physical effects could enable identification of environmentally advantageous concepts.

Key words: environmental effects, working principles, principle solution, physical effects, TTS

1. Introduction

Adopting environmentally conscious attitude early in the design process enables for the designers to practice environmentally sustainable design or Ecodesign. Performed literature review on topics related to Ecodesign (on-going research developments and Ecodesign methods and tools), resulted in two research trusts. The first focused on explaining the lack of Ecodesign methods and tools suited for application in early product design development stages, and the other, examining the nature and definition of early design stages to accompany Ecodesign objectives. Presented research is addressing the issue of difficulties with estimating environmental effects early in product development process to examine how to qualitatively evaluate product concept alternatives according to environmental effects estimated. Motivation behind enabling the designers evaluate alternative product concepts early in the design process is to be able to reason upon and select environmentally advantageous concept alternatives for further development.

For manufactured products, environmental friendliness is expressed in form of product’s environmental performance (product’s performance throughout its life cycle). Relevant findings point put that availability of information regarding product's life-cycle is of outmost importance when trying to find out about product's environmental performance, since it is necessary for calculating product's environmental impact. In most cases, information about product and its performance during its life cycle is not available in early design stages while developing concepts. That is why in practice, environmental impact assessments are performed retroactively and conclusions about product's environmental impact are made based on "reference" and existing products.

Conceptual design creates particular challenges for environmental assessment. Radical and innovative changes of product's concepts in later design stages acquire additional costs to development process. Objective of the research presented is at identifying product's environmental effects or effects on the environment early in the product development process, so environmentally preferable working principles and solutions can be incorporated into product's concepts. The issue of establishing the environmental quality of products in early design stages, conceptual development particularly, concerns the questions about the general product (concept) description at that point of product development. The solution space, i.e. the degree of freedom to choose solutions [13] and the potential for environmental improvements is higher in the beginning of product development when ideas and conceptual solutions are open. The solution space is narrowing as the general product features are established and more details are determined. Working principles of the product, as well as establishing the flow of energy and material between the future product, human systems, and environment are the basis for establishing future environmental effects of the product.

2. Background

Product design development process can be described as a problem-solving process [2]. The designer is trying to go from abstract to concrete while performing design tasks and decomposing design problems to smaller ones. Gradual and causal synthesis allows for designer to understand the object of design and to fine tune according to the design requirements [11]. In general, there is a certain sequence of design stages in product development, processes that include conceptual development, embodiment design and detailing design stage. Planning usually precedes the design development process, which is followed by production. In conceptual design stage of product development, information on product's function, working principles, physical effects, and solution principles [6] are used to determine the predicted capability, behaviour and performance of the product, which is checked experimentally in later development stages, once final form (physical embodiment) of the product is established. For most product development processes performed in practice, it is common that a certain sequence of procedures (design activities) is accomplished: identifying needs, developing product functional requirements and specifications, deriving the functional structure, formulating several product concepts variants and selecting one concept for further development and embodiment design aided by evaluation and assessment procedure, tool or model. Once embodiment design solutions are established (form; structure and components), fundamental product features are set, manufacturing processes defined and the details of implementation and manufacturing are incorporated in the production plan. When design has finished, production begins, and so-called environmental impacts are 'locked in' for the life of the product [14].

2.1 Motivation

Early design stages are widely believed to have the most influence in defining environmental aspects of products, as well as cost [8]. Since environmental considerations need to be taken as an important criteria in product development, most authors agree that introducing them early in product development process is a preferable strategy [24]. Lindeman and Lorenz [17] also consider early design stages decisive, since *'most impact on definition and structure of the product developed takes place previous to detailing and embodiment phases'*. The most (up to 80%) of the environmental, social, and cost factors for a product are determined in the conceptual design stage [8], so here is where truly effective improvements can be made. McAloone and Bey arrived to the similar conclusion regarding environmental effects particularly. Further they explain that by establishing root causes of product's environmental impacts occurring throughout the course of product's lifecycle, proposals for environmental improvements can be made [20].

Another observation about the early stages of product development is made by Sherwin [24]. Although the early stages (pre-specification, product planning, concept design and strategic design) are recognised as important for environmental improvements and innovations (especially radical innovations, which are adversely different from incremental innovations and redesign), there is *'a shortage of work and tools and working practices or research'* at these early design stages.

2.2 Ecodesign and early design stages

In early design stages, product- related information, for example about the product's predicted performance in each product's life cycle phase, are unknown or vague [9]. Feasibility of establishing environmental effects early in the product development process depends on information availability in particular product development stage. In novel product development, information on existing products is often used to predict life cycle performance of a future product. Considerable efforts from Ecodesign and Design for Environment research community have been made on development of methods and tools for environmental impact assessment, enabling evaluation of concepts according to environmentally related data, and assisted by methods and tools for decision-making [21].

There are several ways of introducing environmental considerations into product development process. In Bovea and Perez-Belis's overview of tools for integrating environmental requirements, the tools are classified according to design activities that they support, mainly: planning, task definition, requirements setting design activities, function description, design alternatives generation and comparison, and best alternative selection [5]. When choosing between concept alternatives, evaluation criteria can be set to accompany separately declared environmental requirements (or requirement specifications). However, it is difficult to specify and quantify environmental requirements and specifications in these early design stages. In the case of qualitative concept evaluation, criteria for evaluation need to be elaborated and concrete as possible.

Considerable efforts have been made on development of methods and tools for concept evaluation that would include environmental- related data about the concepts being developed and decision-making purposes [21]. In concept development stage, product's structure, fundamental features and manufacturing processes are not established yet, product's life cycle is unknown or vague, so establishing environmental profile of the future product is possible only by making assumptions and using information from previous or existing products. Lindahl summarizes the reasons for a considerable small number of Ecodesign tools' applicability to conceptual design development. The main reason is in the lack of knowledge about the product at this stage of product development [15]. Andersson explains the real nature of product concepts as the reason why quantified environmental effects can only be assessed in later design stages: *'A memory rule that can be used is that design* *concepts have capabilities, but no capacities, which means that an effect can be anticipated but questions concerning the quantity of the effect are postponed to subsequent design stages'* [1].

2.3 Assessments of environmental impact in product development processes

Environmental impact assessments are characterized as being both detailed and specific when dealing with environmental considerations of products, services and processes. The most prominent method in the group is Life Cycle Assessment or Analysis (*abbr.* LCA). LCA provides insight into the main causes of the environmental impact of a product or 'how the product contributes to environmental problems'. Products indirectly or directly cause environmental problems. Growing demands for improved or new artefacts, services or systems and increasing individual, organizational and/ or social needs result in environmental problems such as pollution and resource depletion becoming larger and environmental issues becoming more complex. Getting an overview of environmental effects is essential when developing green design solutions, and mainly because in that way, environmental improvement proposals can be made [20].

Life Cycle Analysis (LCA) is most usually used method for calculating environmental impact, and according to Bevilacqua et al. [4], the only method for measuring environmental impact throughout entire product's life cycle. Main steps of LCA include: (1) setting the inventory of relevant energy and material inputs, (2) evaluating the potential environmental impacts associated with inputs, and (3) environmental releases and interpreting the results of the inventory and impact phases according to the objectives to the study. However, it is necessary to understand that this type of assessment can only be performed when the fundamental product's features, characteristics, and manufacturing processes are defined, and when the product's life cycle is established and known. Environmental impact assessment methods are difficult to implement in early product development stages, conceptual design stage particularly [21]. Important, reliable and accurate information is required, for the information about the product to be considered sufficient for performing life cycle and environmental impact assessments. When improving already existing products, LCA is used for making comparison to the old ("reference") product with a well-known life cycle [25]. LCA results can indicate where the environmental problems and 'hot spots' are, but it's purpose is not to provide guidelines or suggest ways to solve them [26]. This conclusion is not limited to LCA only, but to other analytic qualitative methods such as Environmental Effects Analysis (*abbr.* EEA). Objectives of EEA are to identify and evaluate significant environmental impacts of a product in an early stage of development project and make suggestions for environmental improvements, so the negative environmental impact of the product's entire life cycle may be prevented or limited in a cost-effective way [16]. Although the results of EEA point out to environmentally preferable choice (according to designer defined environmental requirements), comparison of, for example two different technical functions of the same product cannot be performed using this method.

2.4 Theoretical foundations and research approach

Number of theoretical approaches to interaction of products to their surrounding (environment, human beings, other products, systems...) define influences (effects) of products on the environment and vice versa. Multidisciplinary theories and approaches provide for different ideas and descriptions of ecosystems or systems in general. For example, holistic idea prevails to the study of ecological systems in ecology with several interdisciplinary fields describing interactions and transactions within and between biological and ecological systems. The theory of technical systems [11, 12] was developed as an overall theory of engineering design, with origin in general systems theory. Systems approach and the ideas with origins from disciplines concerned with study of systems, are often applied when coping with complexity issues in complex systems.

As described by F. Capra, Santiago Theory of Cognition, specifically theory of autopoiesis is tasked to explain the nature and behaviour of living and non-living systems in a distinctive way. The emphasis here is on living systems whose self-generating and resilient characteristics are distinguishing them to non-living systems, also a part of the autopoietic network. The theory of autopoiesis *'identifies the pattern of networks as a defining characteristics of life, but does not provide a detailed description of the physics and chemistry that are involved in these networks'* [7]. Even though, the theory of autopoiesis is more suitable for analysis of living systems, it serves a valuable approach to non-living systems. According to it, non-living systems react to changes from their surroundings according to a linear chain of cause and effect. Effect here means result (output to the process of reacting, according to the behaviour of the non-living system), and cause can be defined as the input given to the non-living (technical) system.

3. Establishing working principles and effects - the basis for environmental effects estimation

3.1 Design evolution from conceptual to embodiment design

Main goal of the concept development in product development processes is to define product's structure. After a series of iterations between concept formulation and evaluation has yielded one or more desirable concepts, the process enters the embodiment design stage and after that, the detailing design stage. Continuing improvements of the design solution results with the origination of basic form properties allowing embodiment design. Since at that point, information about product's structure, shapes, materials, dimensions and surfaces is available, so environmental impact assessment can be performed. This allows that conclusions about possible environmental improvements can be drawn. As illustrated in Figure.1, the quantity of relevant design information (including environmental information) is increasing as the conceptual design development progresses from early requirements and functional definition to general and detailed design.

In addition, information about the use of environmental resources allows for conducting environmental impact assessments. These transformations of energy and material throughout the product's life cycle [23] are mainly dependent upon manufacturing processes, thus product's structure and embodiment.

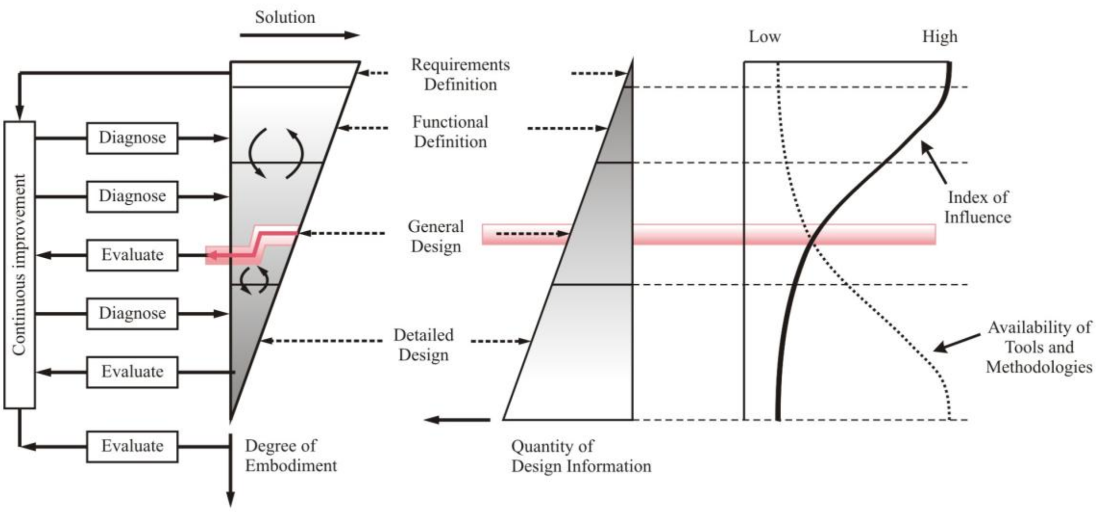


Figure.1 Degree of embodiment of design versus quantity of environmental information [23]

3.2 Product's life cycle

Each product's life phase can be considered a separate transformation system, as the product itself is undergoing several transformations until its decline and end-of-life [23]. The process of energy and material transformations (environmental resources depletion and processing) is characterized with inputs and outputs along each stream. The physical product passes through generic phases in its lifetime, i.e. *raw material extraction*, *manufacture*, *use* and *end-of-life*. In each life cycle phase *materials* and *energy* are consumed either directly into the product or given off as *waste streams*.

Lu et al. [18] proposed a methodology to cover four stages of product's lifecycle (*extraction*, *production*, *operation* and *retirement*), and product's physical structure is considered on four different levels (*material and energy*, *part*, *module*, *product*). Authors wanted to simulate the changes in physical (embodiment) design (*material and energy - parts - material and energy*), as well as changes in product structure (*part - module - product - module - part*), since both will change (transform) as the product's life progresses. In the extraction phase, materials and energy are obtained from natural resources. When the product reaches the end-of-life phase, a decision has to be made to reuse, remanufacture, recycle or dispose of it [23]. Product's life cycle is considered to be a closed-loop system. Another difficulty of using environmental impact assessments in early design stages is the problem of identifying the waste stream [23]. In early design stages, complete information on material and energy flows and transformations are unknown, unavailable or simply not specified yet [9].

3.3 Technical system's internal transformations

Working principles of the future product enabled by appropriate physical effects, are used to define *'how the product fulfils each function'* and supports functional requirements. According to the theory of technical systems, the purpose of the product is represented by the system of its output effects to the technical process. Basically, when defining the desired effects, designer defines the duties of the future product. Products (technical systems) are the suppliers and facilitators of effects to the main technical process. Effects posed on the transformation process can be material, energy or information, or any combination of those. Product (technical system) in its working (operating) state provides outputs for the operand transformation process [12].

Since internal transformations of the product in its working state (use phase) are performed by the technical system itself, transformations of energy, material and information determine the secondary outputs and other output effects from the technical system towards execution systems including environment systems. To establish secondary output effects from the technical system, chain of internal technical systems transformations of energy, material and/or information must first be defined.

3.4 Technological principles, effects and physical laws

Technological principles are based on physical laws by which the operand transformation sequences are being derived from. Knowledge about technological principles can come from prior experience of the designer or design catalogues. Effects and internal transformation of the technical system can be established in the same way the technological principles are established, and also governed by physical laws. Design and solution catalogues serve as a valuable resource for novice and experienced designers to find and reason upon suitable effects when establishing product's functions, working principles and principle solutions [22]. Methods like TRIZ provide for design guidelines on how to utilize knowledge on physical laws. Žavbi et al. demonstrated how providing with a database of physical laws and effects and possibility of chaining of physical laws and effects, can assist students in generating concept designs [28]. Providing knowledge on physical laws and effects (as well as their combinations), and also of less known or yet unapplied physical laws and effects, resulted in generation of different solutions indicating a high level of variety and a better chance to find potentially innovative solutions.

4. Illustrative example - Laundry cleaning process

Case studies on environmental impact of existing products provide information about environmental impact across product's entire life cycle. The results of conducted assessments are utilized to represent environmental impact in each life cycle phase, so conclusions could be made regarding the contribution of each life cycle phase in overall total environmental impact calculated. Energy-using products (EuPs) have a negative impact on the environment. According to previous LCA cases conducted on household washing machines and automatic washing and spinning machines, emissions to air including greenhouse gases, to soil, recycling, water consumption and pollution can be expected and with majority of environmental impact in the use phase [10]. In case studies of washing machines, Matzen and McAloone also concluded that environmental impact in the use phase exceeds environmental impact calculated in production, distribution and disposal life cycle phase by substantial number of times [19].

In novel product development, design process starts with determining the desired operand transformations and the technical process of laundry cleaning. Effects needed for the technical process are established after defining the operations of the technical process, followed by establishing technological principles for operand transformation leading to desired state of the operand (*laundry*). Knowledge about technological principles enabling desired transformations of the operand is used for establishing technical process, operations and effects. Once the required effects are established, designer defines the execution system for each effect.

The purpose of washing laundry is to loosen dirt from the textile fibres, using detergent or soap releases chemical energy to dissolve the dirt, and by using water again laundry is rinsed off [10]. The technology for cleaning the laundry implies the effects needed. Input operand of the technical process (*cleaning laundry*) is 'dirty laundry' (in existing state) and the desired state of the operand is ('clean').

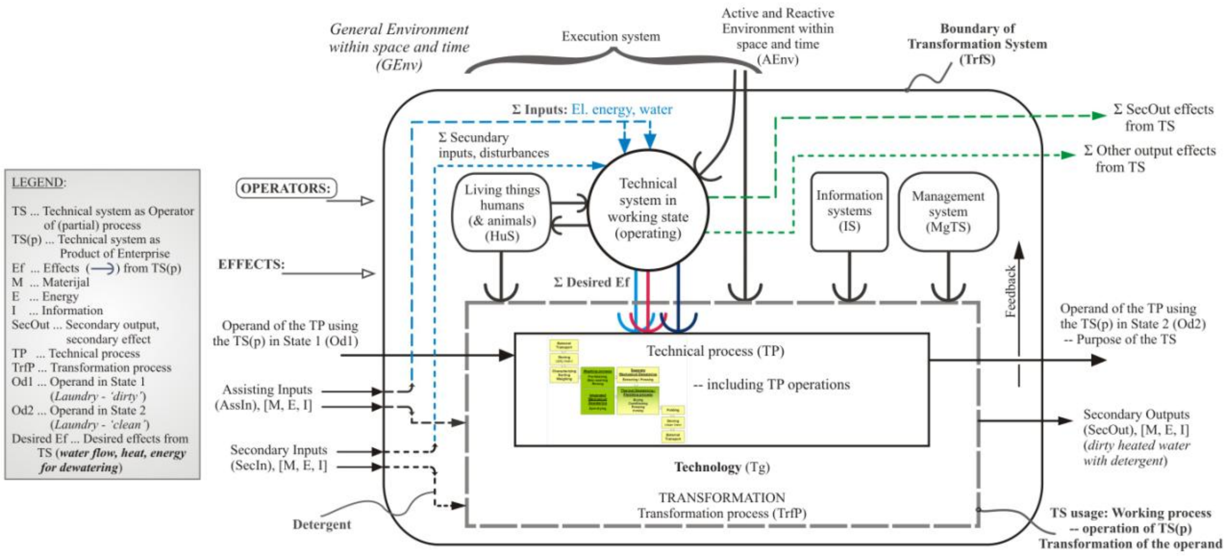
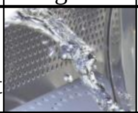


Figure.2 Laundry transformation system - technical system as operator of partial process and product of transformation system enterprise (illustrated according to Hubka and Eder); steps of the laundry process [10]

Among the environmental effects of the technical system, active and passive effects may be distinguished. Active effects have direct, immediate effect on the environment, thus prediction of this effects through a systematic design is foreseeable. Passive effects with delayed effect on environment are built in features of technical system. Those environmental effects are latent through the life cycle of technical system and therefore not easy to predict. The direct environmental effects are stems from desired outputs of technical system, while indirect environmental effects arise from secondary outputs. Desired outputs (effects) conform to the technology chosen for transformation of laundry. Secondary (undesired) outputs or effects can be established by analysing the chain of energy, material and or information transformations which are based upon physical laws. If physical laws governing the effects and internal transformations are established, the assumption is that secondary effects can also be established.

Examples of working principles of products already on the market and also solutions that are presented only as conceptual ideas for future products are summarized in Table.1. Examples illustrate diverse working principles for laundry cleaning using different technologies and in comparison to conventional washing method, e.g. laundry cleaning using warm water and detergent.

Table 1. Dirt removing technologies applied in products for laundry cleaning

No.	Description of the working principle	Illustrative figure	Material and energy form required as inputs	Expected secondary outputs (material)	Main (attributive) physical law or effect
1	Laundry cleaning using warm or cold water and detergent		Water, detergent, heat, agitation laundry and rinsing force	Dirty heated (or cold) water with dissolved detergent and dirt	Chemical reaction of heated (or cold) water and detergent onto dirt particles and stains
2	Laundry cleaning using foam		Water, detergent, air, agitation laundry and rinsing force	Dirty water with dissolved detergent and dirt, air	Using foam (water, detergent and air) to dissolve dirt (chemical reaction)
3	Laundry cleaning with steam		Water (high temperature and pressure), agitation and rinsing force	Dirty heated water with dissolved dirt	Using steam to loosen textile fibres (water on high temperature and pressure)
4	Laundry cleaning using polymer beads		Water, polymer beads, agitation laundry force	Water, polymer beads with dirt	Polymer beads agitate, attract and transport away dirt from textile surfaces
5	Laundry cleaning using ionised particles		Water, ionised particles (silver, water, ...)	Water with dissolved dirt and ionised particles	Ionic action (negatively-charged ions attract dirt from fibres)
6	Laundry cleaning using ultrasound		Water, ultrasonic sound waves	Water with dirt particles	Cavitation effect
7	Laundry cleaning with liquid nitrogen		Liquid nitrogen (dry ice), carbon dioxide	Liquid nitrogen (dry ice), carbon dioxide, dirt	Cryolysis (breakdown of dirt by freezing it to very low temperatures)

5. Discussion

Feasibility of establishing environmental effects of the future product early in the design process depends upon whether certain information about the product is available, such as information on planned utilization of natural (environmental) resources. In early design stages, level of product concretization is low and description of the future product is abstract, so information about the influences of the future product on the environment is not available prior to establishing product's structure, manufacturing processes and product's life cycle. However, some environmental effects can be anticipated, and these are related to product's purpose and duties.

The future product is represented as a constituent of a larger transformation system as is illustrated in Figure.2. Since designer defines all transformations in the process, by establishing technical principles of the laundry cleaning process, some environmental effects are expected (secondary outputs from the whole transformation process). On the other hand, secondary outputs (effects) from the technical system depend upon the technical system's internal transformations and how do the conversions (transformations) of input energy, material and/or information occur to provide for desired effects.

All secondary effects that are (1) enabled by or assisted by inputs from the environment (from natural resources), and (2) their output flow towards the environment systems can be established, are environmental effects. Further, secondary outputs (effects) from the technical system are vague and unknown prior to establishing the chain of internal transformations of the technical system.

Since transformations of energy, material and/or information is based upon physical, chemical, or biological law, relation or phenomenon [27], the effects are also based upon the corresponding law, it is able to anticipate them. Based on above given assumptions a system for estimating environmental effects can be managed.

The assumption is that variant chains of energy, material and or/ information transformations of acquiring effects, will result also in different secondary outputs or environmental effects. In this way, secondary outputs or effects could provide for a measure of eco-friendliness of the solutions and concepts in early design stages, since at that point product structure, components and manufacturing processes are yet not defined. This line of thought is based on expectation that different solutions of the internal technical system's transformations accompanied by suitable physical laws, will differ in environmental effects exerted onto active and immediate environment. This enables comparison of variant solutions to realizing effects based upon analysing corresponding physical laws governing the desired transformations of energy, material and or information. The utilization of physical laws and effects to establish different embodiment design solutions is been recognized in the research conducted by Žavbi et al. [28]. Establishing different alternatives of internal transformations of the product (the way of acquiring the desired effects) presents an opportunity for developing innovative solutions and concepts, so enabling significant deviation of product concept from its formal archetype.

Working principles or 'how the product fulfils its function' are elaborated into principle solutions recognized as being suitable for delivering analogous functions and effects, and structural arrangement. Establishing working principles and principle solutions is considered to be the first level of concretization in design development process, because it requires that form properties are defined (material and geometric properties). As described in the work of Brunetti and Golob [6], five elements are required to define a principle solution: (1) effect described by (2) physical laws, (3) input and output flows, (4) corresponding function or functions for a particular principle solution, and (5) effect carrier (solid, fluid, gas or plasma).

Corresponding physical laws describe the relations between input and output flows (main and work flow inputs and main flow outputs and side effects), and form properties such as material and geometric properties describe the initial and final (desired) state of the effect carrier. Form properties instigate according to the relation between the effect and effect carrier, and mainly dependent upon the physical law governing the effect. Embodiment design solutions are in subsequent steps of product development worked out into components and parts, so allowing for more information available on materials and possible manufacturing processes. Available information can then be used to conclude upon product's life cycle and structure and allow for making changes as described by Lu et al. [18]. When information on materials, components, production processes, product's life cycle and environmental resources is available, the amount of information is sufficient for conducting environmental impact assessments allowing for a more detailed insight into environmental effects and environmental impact.

Materials selection and embodiment design (components and parts) obviously contribute to product's overall environmental impact, thus important criteria of product's 'goodness' comes from the product's life phases [11]. For products with use-intensive life cycle phase, the majority of environmental impact is found in the use phase. The product's performance in the use phase is highly dependent on how the internal transformations or chain of energy, material and/or information transformations is performed, e.g. dependent upon the general design (Figure.1) and working principles.

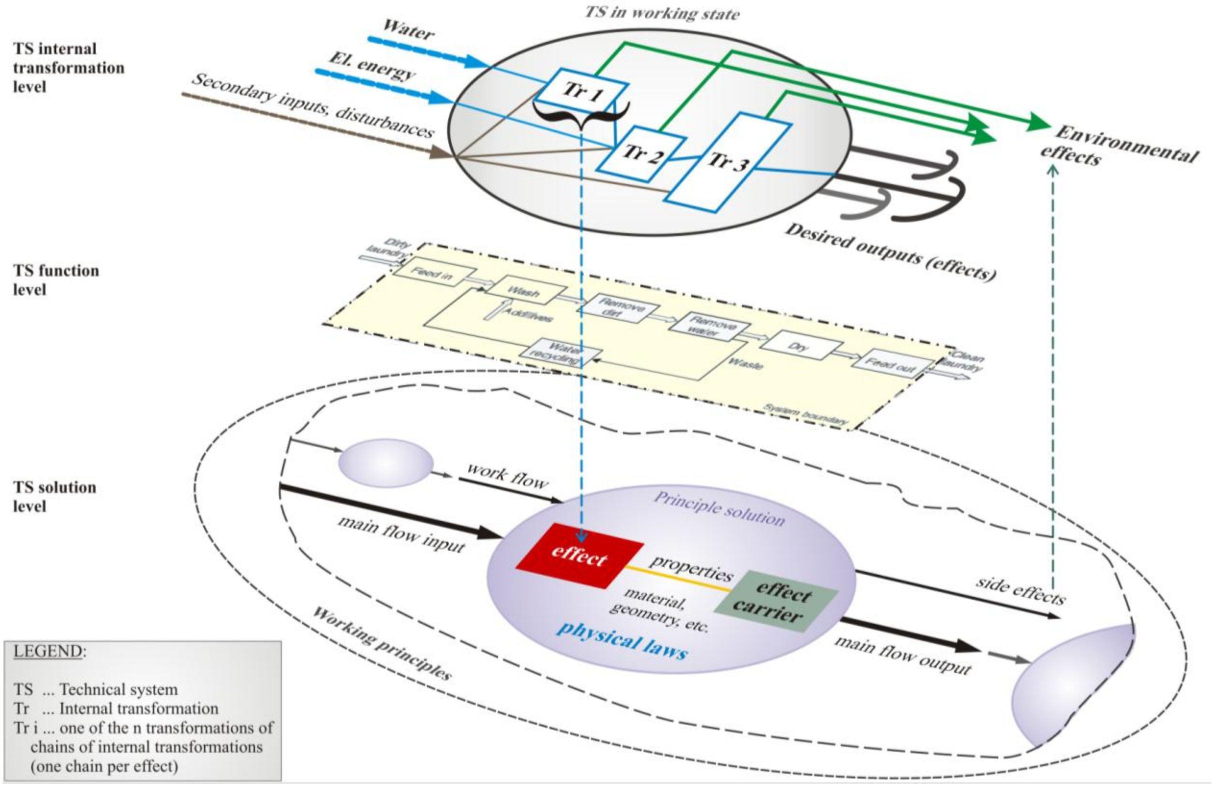


Figure.3 Relationship between internal transformations (technical system for laundry cleaning process, see Figure.2) and principle solutions; function structure from [3]

6. Conclusions and future work

Proposed research is motivated by the need for alternative methods for estimating environmental effects early in product development process and prior to establishing embodiment design solutions when in most cases, information about the product is not sufficient for conducting quantitative environmental impact assessments. Therefore, establishing the criteria for evaluation of solutions and working principles should exclude quantitative assessment methods. In order to establish the approach for estimating product's environmental effects, products are described as suppliers and facilitators of effects to perform some desired transformation of energy, material and/or information, e.g. its purpose. An illustrative example of a laundry cleaning process demonstrated that secondary effects from the future product (technical system) are unknown and vague prior to defining the chain of internal transformations of the technical system to acquire the desired effects. After establishing the relationship between technical system's internal transformations, working principles and principle solutions, the correlation is made between secondary effects (outputs) of the internal technical system transformation (i.e. environmental effects) and side effects of corresponding principle solution.

Since physical laws govern the effects, future research will focus on establishing environmental effects according to chosen effects, physical laws and effect carriers (described by material type) available in design catalogues and solution catalogues. According to environmental effects estimated in that way, designers can reason upon environmentally preferable solutions among different alternatives. Furthermore, if variant solutions of acquiring effects would be made, the estimations would allow for comparison of different effects (governed by physical laws), principle solutions and subsequently working principles from an environmental point of view.

Future work aims at finding a way to conclude upon environmentally advantageous concept alternatives by setting environmental criteria for comparison of working principles and physical effects. More importantly, this would allow for designers to conclude upon less sustainable solutions, so eliminating them from the pool of potential candidates for further development. Ecodesign methods and tools for conceptual design stage will be used for comparing to the results of own evaluation method.

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