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AN APPROACH TO INCREMENTAL INNOVATION THEORIES AND ITS METHODS IN INDUSTRIAL PRODUCT DEVELOPMENT

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ABSTRACT
A quest for powerful tools to support creation of innovative solutions exists in industry. Majority of development efforts aims for incremental development of products, either by means of improved performance in use or during manufacturing process. New concepts or solutions on product's functionality and behaviour (behaviour meaning how the functionality is delivered, response) are needed to bring benefits. Generic product development theories, models and methods are applicable for new product development, as their approach is linear and founded on functional requirements and means to execute them. However, in industry the product development activities preferably start from existing product or concept with pre-determined goals rather than from scratch.
Creativity techniques and multidisciplinary workgroups have been referred in literature as means for creating innovations. However, these methods lack context of technical system and are general in nature and could be used for any problem with assistance of experienced moderator and a group of individuals. These techniques and methods are not included in this study.
An approach from retrospective case study is presented. It was found that the mental process of an innovator follows more problem solving theory than design theory. However, the structuring and verbalization of the problem, in which constraints and resources are considered, do not include multidisciplinary view of different technologies. A new approach is developed based on the assumption of the inventor's mental process. However, further study is required to develop a method, which may foster the introduction of new incremental innovative solutions by utilising integration over technological disciplines.

Keywords: product development, incremental innovation, design methodology

1 INTRODUCTION
During the execution of product development projects, any powerful tool to support creation of innovative solutions is welcomed in industry. In the literature, innovation theories and methods are presented in different contexts of product, engineering and innovation. However, in industrial development projects, the practise may be more relying on creativity techniques and multidisciplinary teams rather than innovation methods. Even, if methods are applied, only few theories relate how innovative solutions really can get their birth at concept or solution level.
Majority of development efforts aims for incremental development of products, either by improved performance during their use or manufacturing process. The benefits, which will be introduced to the market on product's functionality and/or behaviour, call for new product or solution concepts. Generic product development theories, models and methods are applicable for new product development, starting from need surveys, "market pull", or from technical opportunities, "technology push" type projects. However, preferably in industry, the product development activities start from existing product or concept with pre-determined goals rather than from scratch. Additionally, the knowledge and history in developers' mind schemes cannot be erased or neglected for the development tasks.
Questionable is if generic product development methods are applicable for purposes, where existing concepts and/or developers' knowledge and experience set the premises for the development.

Motivation of this study was the curiosity, how, if possible, to follow and replicate the mental process of an innovator and find means or guidelines for a product development engineer. Creativity

techniques and multidiscipline workgroups are generally referred and promoted in literature as means for creating innovations. However, within technical systems, these methods lack context and are too general in nature. Methods are not specifically for developing technical systems nor for incremental development of existing concepts, in which the technical context is dominant – they could be used for any problems. These techniques and methods are not included in this study.
This paper focuses on innovation theories and methods, which contribute on technical or design context and could be used by development engineers on incremental product development tasks. A retrospective case study was analyzed to evaluate, if any methodological elements may be identified in mental process and bring out insights how intuitive solutions get their birth.

2 DIFFERENT CONTEXTS OF INNOVATION

Literature presents contributions to different aspects, how product innovations relate to product origination process. By its definition, the prerequisite of innovation is a successful commercial application. How and when the success is measured, depends on the context and the view of stakeholders, but is finally justified by benefits, either to user or manufacturer. Different types of innovations have been identified and classified according to their impacts or achievements, introduced namely with terms like radical, incremental, modular, architectural or disruptive innovations [1],[2],[3].
Innovations exist at all levels of business or engineering environments. The review of different studies and articles reflects the applicability and position of the innovation theories and methods. An approach is shown on Figure 1, where different theories may be positioned on three dimensions. Closest to the origin, where the most concrete and detailed technical environment exist, describes the practical work and impact area of a design engineer (coloured triangle). Progression on each axis from origin broadens and abstracts the impact and influences of particular task, problem or solution.
Different dimensions are later evaluated in respect how they contribute and support the creation of concepts and solutions, particularly during incremental development.

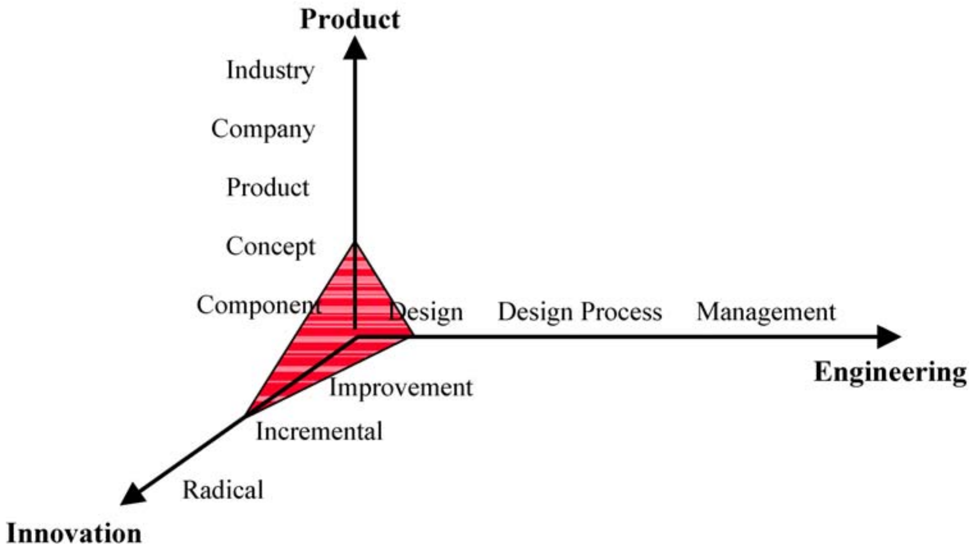

Figure 1. The dimensions of design engineer's sphere of influence

2.1 Product dimension

The product dimension describes the different levels and aspects of product concretisation and business. Further the distance from origin comes, the technical context decreases and business strategy, management and marketing become more relevant. Business literature [1],[2] presents multiple aspects of innovativeness changing industry and success stories and failures of companies. Numerous studies of survival and death of enterprises during their existence have been done. Common to these studies is, that the different types of innovations are considered in respect to organizations and business environments, but the technical context for product design has been minor.
The most interesting context for industrial development engineers is naturally among the technical system, in which the quest for means how to generate new solutions, product concepts or even innovations is mostly needed. However, only few studies or methods penetrate deep enough into

technical content of a product. Product architecture, product family and modularization aspects have an important role on product strategy, but diverge from designer's task on particular design problem.
The product innovations are considered to get their birth in the beginning of the product origination process, on higher level where the market or customer needs are considered. However, the majority of product development activities in industry are aimed to existing products, initiated more likely close to the origin on Figure 1, to provide new solutions in sub-level of products

2.2 Engineering dimension

Engineering dimension in literature [5], [6] is presented by product development processes with various methods for abstracting the design task and developing further on the functional solutions. Different methods and models may be used for decomposing the technical system into structures: transformation processes, functions, organs and parts.
An important stage during the design process is, when conceptual design alternatives are generated and evaluated. Systematic design process, like VDI2222, provides inputs, tasks and outputs for each design phase for controlling the process, but not much support or means for generating solutions. Consequently, processes and tools are more applicable for new product development. Typical advisable means in literature, which are referred for finding solutions during conceptual design are, creativity techniques, morphologic graphs and construction catalogues. Once the design becomes more concrete, methods and tools for generating innovative solutions shall be more context sensitive. However, none of the earlier mentioned methods support incremental concept development.

Pugh [5] focuses on systematic design process and distinguishes the differences between static and dynamic designs. Engineering on static design, where generic base has been reached, the concept is already given. The product specification is written on assumption, that few changes or any is expected, e.g. concept is defined prior to specification. With dynamic design the specification is generated from analyses of the market and users' needs and product concept will follow the requirements. However, the creativity and innovations in design are seen more from organizational and engineering system point of view, where multidisciplinary approach has an important role. On design methodology Pugh distinguishes qualitative and quantitative methods, namely on first group analogy, inversion, attribute listing and T-charts and on second group non-numerical decision matrices. How these methods contribute in practise for incremental development is questionable – can innovations be initiated by analysis?

Suh [6] formalizes the design process as mapping between four domains; customer, functional, physical and process. Functionality is the mean to satisfy customer requirements and shall be defined in a solution-neutral way. Conceptualization takes place after defining the functional requirements and is described as mapping process from functional domain to physical domain. At this stage, the solution (concept, product architecture) is defined by means of design parameters. Different approaches shall be used in case of improving existing products or new innovative products. In search for design parameters (DPs) while mapping from functional domain to physical, methods like benchmarking, reverse engineering, QFD and copying are suggested. Within these methods, creativity and innovations are rather distant.
Suh identifies also, that the representations of technical systems have the challenge in case of multi-disciplinary products. Development should be done by integration; design activities should have simultaneous consideration of hardware and software. Different models have been presented to provide systematic breakdown of the product structure from different views. Models of the system are tools to increase technical context and decrease complexity with the problem, but are generally inadequate to show integrations between disciplines.

2.3 Innovation dimension

Innovations can take place in different ways along the product development and lifecycle. Utterback [2] presents the pattern, how the intensity of product and process innovations follows each other within phases as:

- Fluid phase; great deal of experimentation with product design and operation takes place in the beginning of the life cycle

- Transitional phase; major product innovations slows down, product variety gives way for standard designs (dominant design), rate of process innovations speeds up during the product volume ramp-up.
- Specific phase; both product and process innovations slow down, focus on costs, volume and capacity, innovations in incremental steps during the product maturity.

In industry, the products, which have reached the specific phase, bring often the majority of the cash flow. These products provide the backbone to finance new product developments and therefore their contribution margin is under careful follow-up. Companies with established organizations tend to reinforce their capabilities and competitiveness with improvements on existing products Utterback [8]. Henderson and Clark [3] present four types of innovative products:

- Incremental, generated among products at dominant design phase
- Modular, generated among products with dominant product architecture
- Architectural, re-organisation of existing components
- Radical, initiated by new technology

Distinction between the types of innovations may provide some support, in what context or format and how innovations may appear. However, from designer's point of view, main differentiation between innovations is, if the new solution is either done differently or done better. Accordingly, different refers to radical and better to incremental innovation.

One example of a systematic innovation theory is TRIZ, developed by Altshuller [7]. Within this theory, a substance-field analysis acts as an abstracting model and tool to generate innovative "zero sacrifice" solutions utilising contradictions in the system. The backbone of the method is a comprehensive list of physical phenomena, which may be applied to reach the desired transformation process within the problem or functionality. The method is best in applications where either a physical or chemical environment (field) exist in the system. Even with the wide acceptance and commercial applications on the market, developers with modern industrial systems may find methodology laborious or less applicable on engineering tasks on concept or solution level.

3 TOWARDS THE NEEDS IN INDUSTRIAL PROJECTS

Systematic design and engineering process is essential to ensure requirement driven specification, conception, design and execution of the project according to planned schedule and costs. However, the systematic process by itself does not generate nor support the creation of innovative solutions. More often the practical problem in industry is not in developing or improving ideas further on, it is in generating seeds for new ideas.

Many theories and models formulate design process in stages, where customer requirements are transformed into functional requirements and further on to solutions. In process of new product development, the definition of functional requirements is essential, if any earlier product doesn't exist to cope with. However, this is not a typical case in industry - more often the development activities are directed to existing products.

Like presented on several studies [2], [5], the degree of innovations along the product's life cycle follows a path. The strong development stage with numerous product innovations is followed by significant decrease, which indicates that the product design has reached its maturity level, called either dominant or static design. At that stage the technical solution for the main functional requirements is very alike between different manufacturers. Studies show also, that once the maturity of the design has been reached, development activities are forwarded towards manufacturing processes, mainly driven by cost pressure.

Industrial products today consist either small or large systems, including technologies and components from various disciplines. Even if the solution for the main functional requirements may be similar between the products by different make, differentiation takes place at lower level of the product structure. How different manufacturers have ended up to their specific solutions, have to be directed to the stage in design process, where main functional structure was decomposed in to sub-functions and solutions. At that stage the reasons for different solutions may be explained by different evaluation and valuating of the design drivers, past experiences or competences in the company.

Different solutions are not automatically consequences of innovations; by definition, innovation shall include significant benefits (added value) to the user or manufacturer. A typical development project in industry is driven on existing product or concept, initiated either by recognised opportunity (or problem) or severe cost pressure. This type of activity may be called as incremental development, which may occasionally result incremental innovations.

Models of technical systems reflect the linear design sequence, where product requirements are transformed into functional structure. This working sequence has an assumption that the product functionality is satisfied as a result of different sub functions. Some design processes even suggest, that functional requirements and design parameters shall match to reach uncoupled design, which supports further decomposition of functions. This working principle has its merits with robustness and stability, but hardly supports creativity and leads to innovations.
The development process for an existing concept has a different set of sequences [5], because in addition to the concept, solution and part structure, a lot of product experience, information and data already exist. However, as much as design parameters an existing concept provides, how could all this knowledge be used and formulated during the conceptual stage, where abstract or verbal descriptions are converted into technical format – and used as catalyst for generating innovative solutions?

New approach for developing innovative solutions for existing concepts needs something to catalyst creation of ideas. During the incremental development, in addition to known structure and design parameters, the understanding of how the functionality is delivered can be utilized. This kind of data or descriptions on product behaviour is not typically included or expressed in functional requirements or in specifications, because the linear design methodology assumes, that functionality is fulfilled by set of design parameters. The challenge of development teams is to cope with different disciplines and their integration in the machine system, which finally together concludes the functions in a desired manner. This raises the question, how different information of a technical system could be presented or modelled to provide directions for systematic idea generation for seeds towards innovations?

A case study is presented to identify what kind of knowledge and experience is available within the technical system, when the need for improvements of an existing product is faced.

4 CASE STUDY, A HYDRAULIC GRAB

The case is a typical industrial development to an existing, mature product. The target of the development was to improve functionality and reliability of a hydraulic grab attached to an overhead crane Figure 2. The primary use of the crane is to transport community waste from pit to the burning oven.

Figure 2. Overhead crane and hydraulic grab

The functionality of the grab is provided by jaws, which are actuated by hydraulic cylinders. A pump, rotated with an electrical motor inside the grab, generates the fluid power. Power supply from crane is transported via electrical cable, fed from the drum of the hoisting machinery on the crane. The hydraulic system was simplified as far as possible; the opening and closing direction control was organized by changing the rotation direction of the motor. This simplification was made using a specific hydraulic block with relief valves, which open at maximum working pressure at the ends of the cylinder paths. The power system is shown on Figure 3.

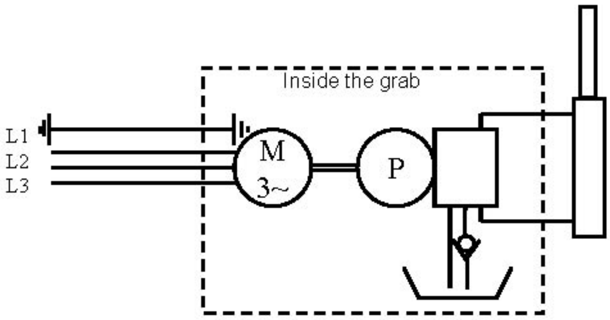

Figure 3. Original grab control and actuating system

The request for the development was continuous problems on power generating system, identified on components as:

– Overheating of the electric motor
– Breakage of the coupling between the motor and pump
– Failures, leakages and jamming of the hydraulic block

The root causes of problems were investigated and recognized to be the consequence of the motor starting and activation of jaw movements against full load and repetitive change of rotation direction of the motor on each working cycle.

As usual, the application consists of constraints to restrict the development task;

- The grab interface design shall not be changed to prevent changeability on existing installations
- Power requirements shall not be greater to affect dimensioning of existing supply system from the crane
- Power supply means to grab, the power cable, shall not be changed to different type due to cable coiling system

Constraints on space, power requirements, cooling, control and power supply have caused, that the problems cannot be overcame with improvements on existing concept by component sizing, an alternative concept was compulsory.

Earlier, the development actions have been done in a single-disciplinary way, e.g. mechanical breakages has been tried to solve with reinforcing the components on mechanical chain. The original concept was simple and done well in the past. However, during the life span of the grab, many upgrades on grab size and capacity has been done and it seems obvious that the concept had reached its physical limits. Earlier development actions during the maturation of the product have not solved the problems.

The new system consists of a general hydraulic pump and valve system with a new control system for actuating the valves (Figure 4). As the main constraint was that only power cable phase wires were available for control commands, the invention was to transmit signals to valve control through them.

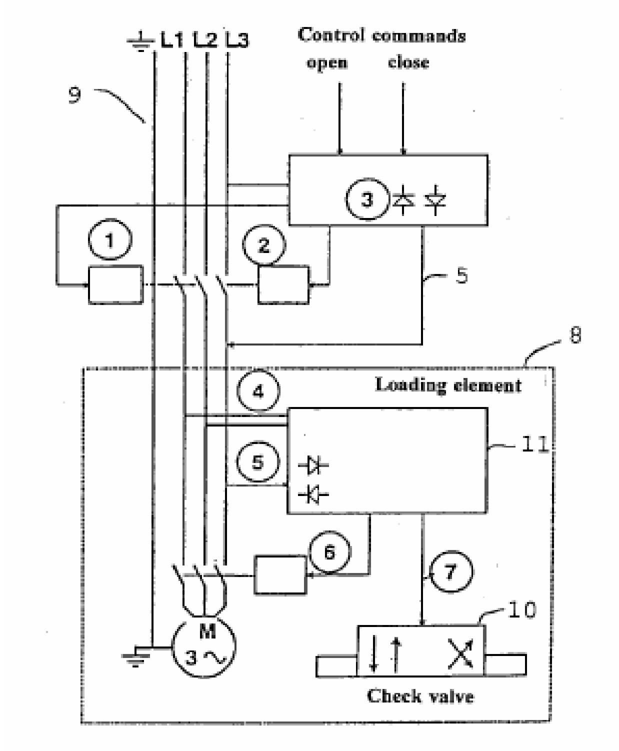

Figure 4. New grab control and actuating system

The content of the commands to valve control were carried by interrupting particular supply phase for few tens of milliseconds, which was then identified in the valve control and interpreted as command to drive grab jaws open, close or keep steady.
The new control system enables to build hydraulic circuit in manner, that continuous run of the motor and pump where achieved. Jaw movements were actuated as the valve directs the hydraulic flow into desired direction. All features and constraints were taken into account, functionality remain and the mechanical problems were solved – additionally the motor size could be reduced due to lower torque requirements at start-up and the response time to action was shortened due to immediate availability of hydraulic pressure and flow.

4.1 Synthesis

The new developed solution was based on an invention and was also awarded a patent. However, the innovation was not created by using any explicit method, at the time of creation it was considered purely as a result of an individual intuition. A retrospective analysis was carried, how innovator may unconsciously collect and organize the information and end up to the new solution. If the mental process could be identified, an imitation provides thoughts and advice for developing a method for more general use during incremental product development.

The start-up of the development process was to analyze the consequences; defects and problems. It was found that the system simplification was the root cause. The operation modes of the grab, jaws open and closed, were executed by rotating the pump the motor back and forth. Repetitive starts of the motor; its acceleration and deceleration generate excessive heating. Also loaded starts and stops against pressure relief valve generate repetitive load peaks.
A linear design approach on this problem would have been to solve it through analysis of design parameters. Starting from functional description to current solution, dimensioning and simulations could be used to find out the operation limits by means of thermal capacity. However, the improvements may come out as heat exchanger, low inertia motor or equal, as results of single disciplinary approach.

The evident solution to overcome problems was rather straight forwarded; typical hydraulic circuit with continuous running motor and pump with separately controllable valve block. However, this was not possible to realize as such due to constraint with the power supply cable – only four wire cable for

power supply was available and no possibility to add wires for control signals. At the time, wireless data transfer systems were considered unreliable due to the rough environment.
Typical feature in industrial development activities is, that a feasible solution to original problem or root cause creates a new problem or is restricted by constraints. The case study showed also this consequence as the original mechanical problem turned to a control problem, or preferably an opportunity. However, the formulation of the problem changed and went obviously beyond the comprehension of the original problem owner.
How did the inventor continue further from this point to develop the better concept? Could methods like decomposition of the functional structure, search of solutions with morphologic charts, QFD or flow modelling provide any assistance? Hardly, because the solution was created through integration between different disciplines, not reachable by linear processing from functional requirements. Commonly used methods like multi-disciplinary workgroups, brainstorming and other creativity techniques were not used, the idea creation and solution were the result of individual intuition, not systematic exploration within and between disciplines.
If we approach the inventor's position as a transform process from problem to solution, the critical question is, how seeds for new concepts can be created in a more systematic way. At first, the process starts more like a problem solving rather than a design process. Referring the problem solving methods [6], [9], the problem verbalization and search of the root cause are the key elements towards the solution. Constraints, contradictions and interactions create the means to search for solutions, providing the guidance what the solution space is and what to change. The problem definition provides deep technical context and it can be utilized for multi-disciplinary search of idea seeds.

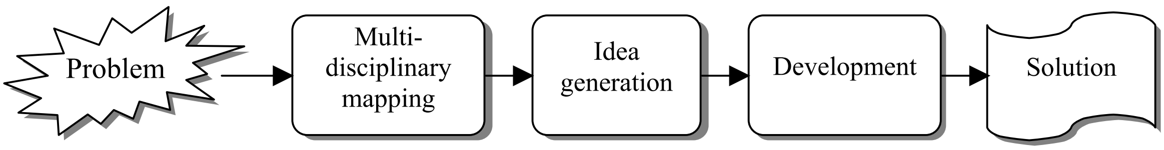

Figure 5. Transform process from problem to solution

It is proposed here, that the inventor may process prior to intuition with a stage, called as multi-disciplinary mapping. This mapping includes the recognition of functional delivery chain, physical phenomena behind the problem, constraints, contradictions and interactions among and between each technological discipline. As consequence of the mapping, possible integrations may be recognised and opportunities for seeds for ideas are provided. Once the identification has taken place, generic principles, rules and parameters can be used to stimulate imagination

5 CONCLUSIONS

This paper deals with the innovation theories and methods, which may be applied with incremental product development of industrial products. The reviewed innovation theories in literature were contrasted with engineering and product contexts, showing the practical working sphere of a design engineer bounded inside the triangle of design-incremental innovation-product concept. The focus of this study has been on that specific area of designing to search for incremental innovation theories and methods, which deal with design context and may be in favour of industrial engineers.

Generic design process and product development models do not sufficiently provide support for development of existing products or concepts. Methods for conceptual design in literature present that the creation of solutions is linear, founded on functional requirements, means to execute them and finally to be designed according to design parameters. Situation, where a design engineer in industry typically is, calls for more applicable tools for incremental development.
The retrospective case study, in which an incremental innovation evolved, is presented. The outcome was, that the mental process of the innovator follows more problem solving theory than design theory. However, the structuring and verbalization of the problem, which consider constraints and resources, do not include technical multidisciplinary view.
In the case study, the development of the solution was fostered with multidisciplinary integration within the design context. Although the innovation consists of an application with control and electrical disciplines, a mechanical engineer made it. No explicit method was used consciously, but

capability of global view of the system was the prerequisite for the inventor's intuition. This confirms, that as presented in literature, creative solutions are more likely to be introduced by individuals having multidisciplinary knowledge and experience. However, even the integration was a result of individual intuition, it was found very attractive and promising mean for generating seeds for innovative solutions.

A new approach was developed to enable an integrative development process, which fosters the introduction of new innovative solutions by utilising integration over technological disciplines in technical system. A specific phase, multidisciplinary mapping, is proposed to be included in the development process to provide context intensive approach before idea generation. The approach, which was identified with the case study, provides a potential method to systematically introduce seeds for product improvements and incremental innovations. On going further study is under process to develop the methodology and results will be presented in future article.

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REFERENCES

[1] Christensen, C. *Seeing what's next? : using the theories of innovation to predict industry change*, 2004 (Harward Business School Publishing, Boston).

[2] Utterback, J. *Mastering the dynamics of innovation*, 1994 (Harward Business School Press, Boston).

[3] Henderson, R., Clark, K. Architectural innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms. *Administrative Science Quarterly*, 1990, 35.

[4] Hubka, V., Eder, E. *Theory of technical systems: A total concept theory for engineering design*, 1988 (Springer-Verlag, Berlin).

[5] Pugh, S. *Creating Innovative Products Using Total Design*, 1996 (Addison-Wesley, Reading MA).

[6] Suh, N. *Axiomatic design: advantages and applications*, 2001 (Oxford University Press, New York).

[7] Terninko, J. *Systematic innovation: an introduction to TRIZ*, 1998 (CRC Press LCC, Boca Raton, FL).

[8] Utterback, J. Dynamics of innovation. *Educause review*, January/February 2004,

[9] Goldratt, E. *What is this thing called Theory of Constraints and how should it be implemented?*, 1990, (The North River Press, Great Barrington, MA).

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