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IDEA – INVENTION – INNOVATION: STRATEGIES, APPROACHES, RESEARCH CHALLENGES

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1. Introduction

Since its beginnings in the 1950ies, Design Theory and Methodology (DTM) has dealt with understanding and supporting (product) innovation. Today, increased innovation activities are paid great attention for many reasons (political, business, environmental, …). Therefore, it is reasonable and useful that the Design Research Community both adapts its findings and proposals to today's requirements and involves itself in ongoing discussions on the generation of ideas, inventions and, subsequently, innovations.

This article tries to contribute to these discussions from a DTM perspective

- by reasoning about innovation strategies (general means to increase the number of innovations),
- by discussing different approaches to generate ideas and develop them into inventions, and
- by drawing conclusions for research challenges in DTM.

The article mainly argues from the point of view of "incremental innovation", i.e. improving existing products – the most common case in practice, but often neglected in scientific literature. Many of the statements are, however, also valid for "radical innovation" (or "new product development", NPD) which, however, is a much more complicated (and in practice quite rare) case.

2. Basic innovation strategies

2.1 Idea – invention – innovation

Following [Schumpeter 1934], "innovation" is an invention (in our context: a new or improved product) which is successfully transferred into practical use. This means that an invention is prerequisite of an innovation, but in addition needs acceptance (with customers/users, more general: in society), profitability and market performance. Therefore, only a certain percentage of inventions will become innovations.

Because the invention stage requires at least some maturity of the product concept, it is useful to introduce an "idea stage" as the first core of an invention. In order to become an invention, an idea needs to be detailed, at least to such an extent that the feasibility of the potential subsequent innovation becomes apparent. In this process, it will again only be a certain percentage of ideas that will be turned into inventions.

In sum, this leads to an innovation concept that has three stages (idea, invention, innovation) and, subsequently, two stage transitions between them (Figure 1).

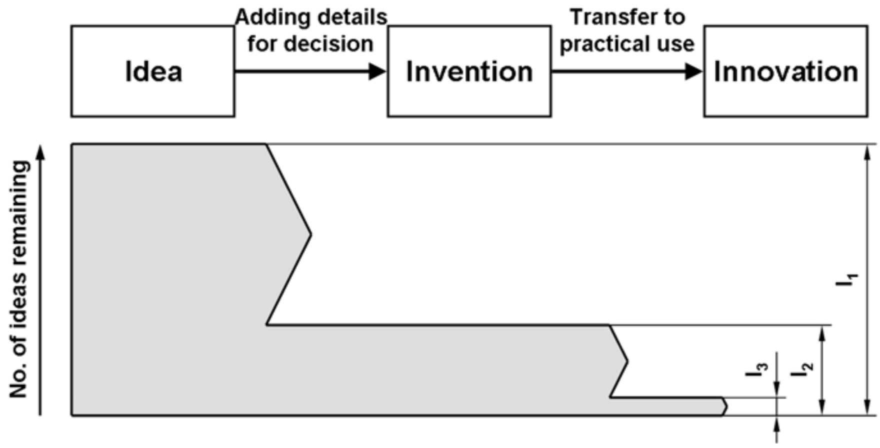

Figure 1. From idea to invention to innovation

To the author's knowledge there is no reliable data available about the percentage of ideas that become inventions and the percentage of inventions turned into actual innovations. It would probably be extremely difficult to investigate such data because the "drop-out" is not properly recorded and because vast differences between branches of industry are to be expected. An experienced designer from industry claimed: "Out of 100 ideas I have, 10 are considered for further development (in the terminology used here: become inventions), and out of these 1 goes to the market (becomes an innovation)." From subsequent observations the author considers this particular "rule of ten" (**I_2/I_1 = 1/10** and **I_3/I_2 = 1/10**) quite plausible for established industries.

Please note that the two stage transitions between the idea and the invention stage and between the invention and innovation stage, respectively, are ***not*** identical with the concept and embodiment design activities as they are defined in traditional approaches to Design Theory and Methodology (e.g. [VDI-Guideline 2221], [Pahl and Beitz 2007]):

- The transition from the idea to the invention stage is usually a mixture between conceptualising and embodiment design. The purpose is to generate enough details to decide about the feasibility and market potential of the idea.
- The transition from invention to innovation, besides finalising the technical details, also implies means to develop and promote the economic performance of the invention.

The theoretical base of our further considerations will be explained in section 3.1.

2.2 Means to increase the number of innovations

From the stage (and stage transition) concept for innovation according to Figure 1 three different approaches ("basic innovation strategies") to enhance innovation can be derived:

1. Increase the number of ideas (**I_1**): If the ratios between inventions and ideas (**I_2/I_1**) and between innovations and inventions (**I_3/I_2**) remain about the same, this will increase the number of innovations (**I_3**).
2. Invest into promoting existing ideas: Follow up more ideas and turn them into inventions (increase **I_2/I_1**). If the ratio between innovations and inventions (**I_3/I_2**) remains about the same, this will again bring more innovations (**I_3**).
3. Push more inventions into the market: Improve acceptance, profitability and market performance of inventions (increase **I_3/I_2**).

The first two approaches are mainly engineering tasks, the third is more related to business strategies and economics.

In the following, the engineering issues will be investigated, i.e. how to increase the number of ideas and how to improve the turnout of inventions derived from ideas. In addition, it will be discussed which dimensions are relevant for a systematic search for ideas and inventions (which, hopefully, then can be turned into innovations). Although this article concentrates on the engineering issues, there will still be some considerations about how inventions influence the business side (improve acceptance, profitability, market performance) and why.

3. Dimensions of invention and innovation

3.1 Theoretical background

The theoretical background chosen is the approach of CPM/PDD (Characteristics-Properties Modelling, Property-Driven Development/Design), where CPM is the product modelling side; while PDD explains process phenomena in product development/design. CPM/PDD has been explained in more detail in several earlier publications [Weber 2005], [Weber 2007], [Weber 2008], [Weber 2010], so only a very brief summary is given here.

The CPM/PDD approach is based on the distinction between the characteristics (in German: *"Merkmale"*) and properties (*"Eigenschaften"*) of a product:

- **Characteristics (C_i)** are made up of the structure, shape, dimensions, materials and surfaces of a product (in German: *"Struktur und Gestalt"*, *"Beschaffenheit"*). They can be directly influenced or determined by the development engineer/designer. May also be called "design parameters" according to [Suh 1990], [Suh 2011].
- **Properties (P_j)** describe the product's behaviour, e.g. function, weight, safety and reliability, aesthetic properties, but also things like manufacturability, assemblability, testability, environmental friendliness, and cost. They cannot be directly influenced by the developer/designer, only indirectly by changing the characteristics.

Characteristics and properties are two different concepts for describing products and their behaviour, respectively. The duality between characteristics and properties has been used in Design Theory and Methodology for a long time, often using a different terminology, but meaning the same thing: "Internal/external properties" according to [Hubka 1973], later [Hubka and Eder 1996] and [Eder and Hosnedl 2008]; "design parameters" vs. "functional requirements" as used by [Suh 1990], [Suh 2011]; independent/dependent properties according to [Birkhofer and Wäldele 2009]. For reasons not to be discussed in detail, Andreasen's nomenclature "characteristics/properties" is retained here [Andreasen 1980].

The only new aspect of the whole CPM/PDD approach is that this duality is in the ***centre*** of investigations. It is also in the centre of this article, as will be shown in the next section.

Studying the relations between characteristics and properties of a product (or vice versa) is the core the CPM-part (the product-modelling part) of the CPM/PDD approach. However, these relations can only be investigated with respect to the context. To mirror this, one more group of parameters is introduced:

- The relations between product characteristics and properties (or vice versa) can only be evaluated against the background of the existing (or supposed) **external conditions (EC_j)**.
  Examples for external conditions are load conditions for the property "strength", user profiles for "usability", the manufacturing or assembly technology/system for "production", life-cycle infrastructure for "environmental friendliness", maintenance infrastructures for "service and repair properties", even cultural influences on (the perception of) "aesthetic properties".
  As has been discussed in [Weber 2007], the external conditions are caused/defined by systems outside of the product itself ("neighbouring systems", "X-systems"). The "X-systems" that define the external conditions can, besides "hardware" (e.g. the manufacturing or assembly system), also be services (e.g. a particular recycling service that contributes to enhancing the environmental properties of the product). This concept is closely related to the concept of so-called relational properties introduced in [Andreasen and Mortensen 1996].
  As was also discussed in [Weber 2007], besides "Design ***for/to*** X" in the traditional sense there is the approach of "Design ***of*** X", i.e. the simultaneous development of the product ***and*** the X-system:

Based on the duality between characteristics and properties, the PDD-part (the process modelling part) of the approach sees product development/design as a process consisting of cycles, implying the following steps (Figure 2):

1. **Synthesis:** Starting from required properties (**PR_j**), characteristics (**C_i**) of the future solution are established. In practice this is often achieved by starting from existing previous designs, at least adopting some known partial solutions (solution patterns/elements).

(2) **Analysis:** In this step, the properties ($\mathbf{P_j}$, as-is properties) of the current solution state are analysed, based on the characteristics established so far. In this step, the properties that went into the preceding synthesis step are analysed, as well as all other relevant properties (as far as is possible at this time).

(3) **Determining individual deviations:** Next, the results of the analysis (as-is properties) are compared with the required properties, the deviations between the two ($\mathbf{\Delta P_j}$) representing the shortcomings of the current design.

(4) **Overall evaluation:** The development engineer/designer now has to run an overall evaluation, extracting the main problems and deciding how to proceed, that is, pick out the property/ properties to be addressed next and select appropriate methods and tools for the subsequent synthesis-analysis-evaluation cycle.

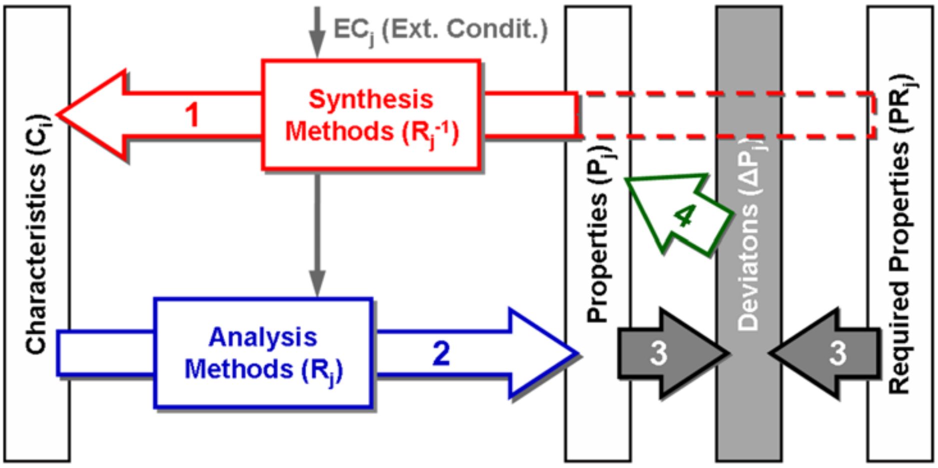

Figure 2. Scheme of the product development/design process consisting of cycles of synthesis–analysis-evaluation steps

Synthesis and analysis steps require appropriate methods or tools ($\mathbf{R_j^{-1}}$, $\mathbf{R_j}$), as indicated in Figure 2. These – implicitly or explicitly – incorporate the external conditions ($\mathbf{EC_j}$). The tasks of synthesis and analysis steps are:

- Synthesis steps start from given/required properties. Their task is to establish product characteristics and assign appropriate values, bearing in mind the existing (or supposed) external conditions ($\mathbf{EC_j}$) which in the process play the role of constraints.
- Analysis steps start from a known/given set of characteristics (structural parameters) of a product. They have the task to determine the product properties (its behaviour). If the product does not yet exist in reality we speak of “predicting” the properties. Again the external conditions ($\mathbf{EC_j}$) have to be considered as constraints.

During the product development/design process, from one cycle to the next both the characteristics and the properties side of the product description are expanded:

- In the synthesis steps more and more characteristics are established and their values assigned (“detailing” the structural description of the solution).
- The analysis steps deliver predictions of the behaviour of the product. In all cycles they deal with the same (set of relevant) properties – but with a modified and/or extended set of characteristics, thus creating increasingly precise information.

As a whole, the product development process is controlled or driven by the evaluation of the “gap” between required and as-is properties at the end of each cycle.

3.2 Leading role of properties

An invention which has good chances to become an innovation can ***not*** be defined via new characteristics (as engineers often tend to think: “a new design”), but is based on new or improved properties: The properties of products are the drivers of inventions (and, hopefully, subsequent innovations), therefore they shall be investigated in more detail.

As there are different types (or classes) of properties which can be addressed, these are defined as the "dimensions" of inventions/innovations. Table 1 shows the main classes of properties of products. The list is compiled from [Hubka and Eder 1996] and many other proposals of authors who have written about Design Theory and Methodology – too numerous to refer to in detail here.
It has to be noted that not all of the properties are relevant for the customer/user – some are "merely" related to the producer (and maybe even other "stakeholders" like society in general).

Table 1. Classes of properties and their relevancefor the producer or the customer/user, respectively

Properties	**Mainly relevant for:**	
	Producer	**Customer / User**
Functions		●
Efficiency, precision		●
Strength, stiffness, stability (mech. products)	●	
Lifetime, durability		●
Safety, reliability		●
Spatial properties, weight		●
Aesthetic properties (look, feel, smell)		●
Ease of use, ergonomics		●
Manufacturing/assembly/testing properties	●	
Transportation properties	●	
Maintenance and repair properties	○	●
Compliance with regulations and standards	●	○
Environmental properties		
– during production	●	?
– during use		●
– during replacement	○	○
Resource consumption		
– during production	●	?
– during use		●
– during replacement	○	○
Cost		
– during production	●	
– during use		●
– during replacement	○	○
…		

● Definitely relevant
○ Relevance depends on situation (life-cycle system, type of industry/product, …)
? May be relevant as a political issue (e.g. company profile)

The list according to Table 1 only contains "top-level headlines" of properties. A particular case would require further decomposition below the "headlines", right down to (measurable) criteria that define "safety", "stability" and other properties for the considered case. As has been argued in [Weber 2008], the author is convinced that the further structuring of properties as well as their relative importance are always specific to individual industries (product classes), often even specific to individual companies. Therefore, no further decomposition of properties is possible on a general level, and is not attempted here.

The structuring of properties is also time-dependent: Societal, economic and technical changes will put properties/sub-properties on or off the agenda – mostly “on” which leads to the rapidly increasing number of properties/sub-properties of products to be considered simultaneously.
The classification of the relevance of properties (for the producer / for the customer/user) is based on the author’s observations and experiences. It mirrors mainly consumer products made in larger quantities. In special areas the relevance of properties for different “stakeholders” might be judged differently, e.g. in areas like one-off design and production or plant engineering (where the work distribution between design/engineering, manufacturing/assembly, service and use might be completely different). In some cases (e.g. medical equipment) customers and users might even be two separate groups (the health care system / the patient) having their individual views on the relevance of properties.
The product properties, as represented by their major headlines in table 1, are quite engieering-biased. As has been discussed by [Mørup 1993] and [Andreasen and Hein 1998], the customer/user may have a completely different perception of the “quality” of a solution (called “big Q”), e.g. merging several “engineering properties” into one “big Q” and/or distorting the scales between “technical” and “perceived” property/quality parameters. In [Deubel 2004] this approach was extended to measure “customer value” – via generalised Kano-curves – in terms of the extra price a customer is prepared to pay for certain properties and to control the whole product development process by this parameter (and not the underlying technical properties as is the case in traditional engineering approaches).
These considerations are not followed-up in detail in this article (which is engineering-biased, as mentioned in the beginning). However, they are extremely interesting with regard to enhancing acceptance, profitability and market performance of an invention, thus increasing its chances to become an innovation.

4. Approaches to invention

Based on the process model for product development/design according to Figure 2, inventions can have three sources of ideas (“starting points”):

- A Starting from Characteristics ($\mathbf{C}_i$)
- B Starting from Properties ($\mathbf{PR}_j$)
- C Starting from External Conditions ($\mathbf{EC}_j$)

Figure 3 illustrates these approaches against the background of the – slightly simplified – process model shown in Figure 2; the arrows in the figure depict the respective lines of reasoning following from these approaches. Table 2 lists the approaches, the origins of the respective ideas, steps to perform to come from ideas to inventions, their potentials, and contributions of Design Theory and Methodology (DTM) to support them.
Approach C is usually not considered in literature. Yet it has several variants and, because of the extended solution space (not only focussing on the product, but in addition on the external conditions), provides additional opportunities for inventions and, subsequently, innovations. Therefore, in the next paragraphs some explanations and comments on approach C are made.
In approach C the idea stage is initiated by a change of external conditions that influence one or more properties of the product. This leads to the following sub-cases:

- **C1** In Design ***for/to*** X the external conditions are given (input values, see Figure 2 and Figure 3 A, B, C1, C2), they govern analysis and synthesis steps in the product development process. If they change the analysis of the related property changes, even if the characteristics of the product remain unmodified.
  If properties are affected to the worse action must be taken to counteract – usually by modifying the characteristics of the product (synthesis) in such a way that the same or an improved property profile is achieved. The classic example is changed/changing legislation that leads to a product not qualifying for the new standards anymore and, subsequently, necessitating changes on the characteristics’ side.
- **C2** However, Design ***for/to*** X in the true sense would mean that – based on the same or modified required properties – the characteristics can be changed. Afterwards, a new analysis step is required in order to evaluate whether the changed design meets the requirements and whether other properties are affected.

The example here is a new manufacturing technology, e.g. hydroforming, which on one hand necessitates considerable design changes, but on the other hand allows for improved properties in several respects (strength, reduced assembly cost, etc.).

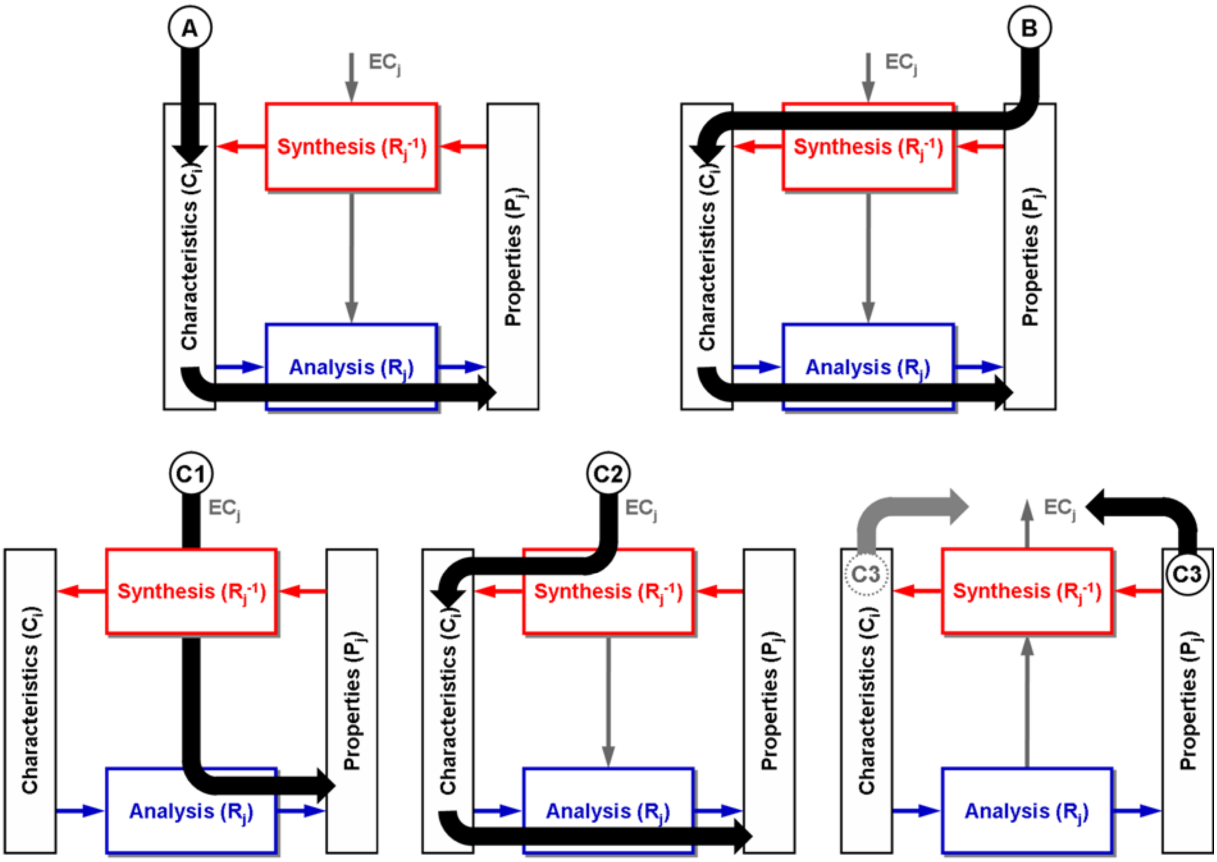

Figure 3. Approaches A, B, C to enhance inventions; note three variants of approach C (C1-C3)

C3 In Design ***of*** X, the external conditions are not a priori fixed; instead, external conditions may be defined (reversal of the **EC**$_j$ arrows as shown in fig. 2). As the external conditions influencing the product are the result of the neighbouring X-system's properties, this means nothing else than posing requirements (required properties) on the X-system. These have now to be realised by establishing/assigning the characteristics of the X-system, i.e. developing the X-system along with the product.

C1 and C2 require idea generation by **scanning** changed/changing external conditions. This can be seen quite clearly adopted by innovative, usually large companies. However, it could and should be more systematically developed and brought into a larger portion of industry, notably into small and medium-sized companies.

Table 2. Approaches to invention A, B, C - overview

	A – Starting from characteristics (C_i)	B – Starting from properties (PR_j)	C – Starting from external conditions (EC_j)
Idea defined by:	Modified characteristics (design parameters, $\mathbf{C_i}$), i.e. a change of the design	Modified requirements (required properties, $\mathbf{PR_j}$)	Modified external conditions ($\mathbf{EC_j}$), e.g. availability of new technologies or "designing" new technologies simultaneously with product
Next steps:	1. Analysis: Determining (all) as-is properties of modified design 2. Evaluation: Checking which properties are affected and in which way 3. Decision: Idea worthwhile to pursue?	1. Synthesis: Establishing/assigning modified characteristics (changed design[s] that meet the requirements, maybe several solutions) 2. Analysis: Determining (all) as-is properties of modified design(s) 3. Evaluation: Checking whether requirements are met; checking whether other properties are affected and in which way	Several approaches: – "Design for a changed X" (C1, C2) – "Design of X" (C3) See text for details
Potential/ outcome:	Can produce more ideas ($\mathbf{I_1}$) Does not necessarily affect the ratios between inventions and ideas ($\mathbf{I_2/I_1}$) and between innovations and inventions ($\mathbf{I_3/I_2}$)	Can increase the ratios between inventions and ideas ($\mathbf{I_2/I_1}$) and between innovations and inventions ($\mathbf{I_3/I_2}$), especially if started with customer/user-related properties (Table 1)	Can produce more ideas ($\mathbf{I_1}$) Wider perspective than approach A because product **and** external conditions are considered $\Rightarrow$ even more ideas Does not necessarily affect the ratios $\mathbf{I_2/I_1}$, $\mathbf{I_3/I_2}$
Comments:	Probably most common approach (change of an existing design)	Most promising approach, especially if customer/user-related properties are in the centre Quite challenging approach (because synthesis has to be performed first)	Usually not considered in literature The case of "Design of X" (C3) links to innovative Product-Service Systems (PSS) as the new/modified X-system could be a service
Tasks for DTM:	Develop methods and tools that help creating many variations of characteristics (= many ideas, many changed designs) Develop particularly quick methods and tools to analyse and evaluate properties to enable quick decisions about feasibility	Provide synthesis methods Broader spectrum of properties to consider: – Not only functional synthesis (like in traditional Design Methodologies, e.g. [VDI 2221, Pahl & Beitz 2007]) – Extensions of DfX methods and tools to customer/user-related properties (e.g. safety, reliability, aesthetics, ease of use, …) Integration of such methods into DTM	Clarify the role of external conditions (and neighbouring X-systems that provide them) In addition to traditional Design for X methods: Provide methods for Design **of** X (i.e. developing product and X-system simultaneously) As services play an increasing role as new X-systems: special attention to development methods for Product-Service Systems (PSS); Support of "make or buy" decisions for enhanced or new X-systems

C3 is an interesting case for two reasons:

- Idea generation by ***defining*** changed/changing external conditions may not only mean developing new or modified material X-systems (e.g. manufacturing technologies/systems), but increasingly new or modified services. This is one key to developing innovative Product-Service Systems (PSS).
- Many X-systems are not in the responsibility of the product developer. Therefore, approach C3 often implies a "make or buy" consideration. This is particularly true if a new or modified X-system is or incorporates a service component where traditional hardware-oriented companies may not have experiences.

With view to C3, several recent examples can be observed – all regarded as "highly innovative": New functions in mobile telecommunication have only been possible by realising several additional services which were entirely non-existent before and which today are often by far the more attractive business compared to the material product (the "cell-phone") itself (e.g. map digitalisation services for navigation systems, services to provide text/music/videos, a whole new market for so-called apps, etc.).

5. Summary and conclusions

This article tries to contribute to the discussion about innovation and innovation methods from the perspective of Design Theory and Methodology (DTM) by reasoning about innovation strategies and approaches and by drawing conclusions for research challenges in DTM. In contrast to many other contributions, this article has its main focus on "incremental innovation", i.e. improving existing products. Many of the statements, however, are also valid for "radical innovation" (or "new product development", NPD).

The question how to generate ideas as the core of inventions and innovations has been a topic of Design Theory and Methodology (DTM) since its beginnings. Therefore, it is reasonable and useful that the Design Research Community both adapts its findings and proposals to today's requirements and involves itself in ongoing discussions on innovation. [Ericson et al. 2010] have shown impressively that in DTM-related conferences like ICED (International Conference on Engineering Design) and DESIGN the number of papers on innovation has grown considerably over the last decade.

In the observation of the author, however, these contributions are split between several conference topics. A more concentrated presentation and discussion in an "innovation and innovation methods" stream could not only increase their visibility and impact, but could also be a platform for a more stringent confrontation of different concepts with the needs of engineering practice – including the concept presented in this paper.

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