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Design methodologies: Industrial and educational applications

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ABSTRACT

The field of Design Theory and Methodology has a rich collection of research results that has been taught at educational institutions as well as applied to design practices. First, this keynote paper describes some methods to classify them. It then illustrates individual theories and methodologies focusing on industrial and educational use. Theories and methodologies that are found most practically useful are "math-based methods", "methodologies to achieve concrete design goals," and "process methodologies", while at educational institutes in addition to these, traditional design methodologies are also taught. The paper discusses this gap between practical and educational usages.

1. Introduction

The field of "Design Theory and Methodology" (DTM) has attracted attention of academic researchers and yielded a considerable number of results. Nowadays, these theories are taught in many engineering schools and reported being applied industrially. This current situation stands in a sharp contrast before the 1970s when design was regarded closer to art than to engineering due to insufficiency of knowledge about DTM. However, since there is a tendency that researchers only report "success stories," it is unclear if they are truly useful. This prevents us from performing vigorous evaluation, and obtaining neutral (in the sense of a third party point of view) overview and understanding.

This keynote paper is an attempt to obtain vigorous evaluation by collectively gathering neutral information about DTM, particularly focusing on applications of design methodologies in design education and design practice. The scope and context of design education focus specifically on teaching engineering design in mechanical, production and manufacturing engineering, while the discussion of design practice mainly deals with discrete products such as machines and consumer products. Another aspect arises from the integration of further domains in mechanical product development (e.g., mechatronics) that requires coordinating and adapting mechanical, electrical, electronics, and software development approaches. However, most of the design methods and models discussed in this article may still be applicable.

To achieve these goals, this paper is organized as follows. Section 2 describes the motivation from the viewpoint of engineering design education and application of DTM. To give an overview of the DTM research results, Sections 3 and 4 describes some classifications proposed in the past. Section 5 illustrates our research method and lists DTM to be described in Section 6 which discusses individual theories and methodologies, highlighting their advantages as well as disadvantages. Section 7 summarizes our findings. Section 8 concludes the paper.

2. Design education and industrial applications

Design education focuses on teaching students how to do the design. The design courses could be offered from freshmen to senior year at universities depending on the curriculum requirements. The key point in design education is "to learn how to design." On the other hand, industrial focus in design of products and systems is "design" itself. This critical difference may lead users to adopting different books and references for their specific purposes as some of the texts are more suitable for design education and others more suitable for applications. For industry, it is quite often that they design products based on a previous version with very few cases in dealing with completely new product development. Companies may have developed an internal manual of product design and development which may base on the methodologies in textbook or open literature with the company product specific needs, standards and knowledge.

In the last two decades, design education in engineering programs in North America, for example, has attracted much of attention due to partially the requirements from engineering accreditation bodies such as ABET in the US and CEAB in Canada and partially realization that fresh graduates had difficulties in

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carrying out engineering design of products, processes and systems in a life cycle context upon graduation. With increasing competition, companies prefer to employ engineering graduates who can perform engineers' duties without significant on-the-job training which had been done in the past. However, industry found that some graduates are not ready for engineering work, especially design of complex products and systems.

In engineering design education, we now have a number of textbooks on design methodologies. These books were written based on mostly the design methods reported in open literature and design experiences limited to the extent that the academics can access. Some examples of such books are systematic design by Pahl and Beitz [98], product development by Ulrich and Eppinger [147], and design process by Ullman [148]. During the last 15 years, the design education has also evolved from academic focuses to more real life design project oriented. Most of the engineering educators have realized that the best way to learn engineering design is doing design. In the 1990s, systematic design of Pahl and Beitz [98], total design by Pugh [102], design for manufacturer by Dixon and Poli [31], and design process by Ullman [148] all served the purposes in design education.

For engineering design practices in industry, engineers and managers are more concerned with the results of design by following specific design process more rigorously to ensure that the final design result meets the objectives of the product design and development projects. For example, a major automotive supplier in North America focused on a design process model that a design team must come up with specific design deliverables in each step of the entire design and development process and have a final design solution in a specific form. On the other hand, a heat exchanger manufacturing company in North America followed QFD (Quality Function Deployment) [92] very closely to check if the newly developed product is competitive with the existing, successful products on the market. Many major companies have already evolved their own design practice models and procedures which depend on their industrial needs such as aircraft manufacturers having very detailed procedures in conducting and evaluating designs.

This brings us to specific design methodologies and analyses them in these context and speculates why the certain methodologies are adopted than others in engineering design education and practices and shed a light for the future research and development in this direction.

3. Classification of DTM

Over more than 140 years perhaps since Reuleaux's work first in 1861 [105] and in 1875 [106], many varieties of design theories and methodologies have been developed and proposed, although it is interesting that there is not a clear definition of DTM. Perhaps, a classic view is that a design theory is about how to model and understand design, while design methodologies are about how to design or how design should be. However, the relationships among individual theories and methodologies are so poorly understood that designers are prevented from choosing a right method to conduct design processes and educators from teaching right methods to teach.

3.1. Design Theory and Methodology

The field of Design Theory and Methodology (DTM) is a rich collection of findings and understandings resulting from studies on how we design (rather than what we design). In other words, DTM is about design processes and activities, rather than about products.

Any scientific knowledge begins with collecting facts through observation. A hypothesis will be generated and tested against these facts. If the hypothesis matches or explains phenomena, it will be considered a law that governs the phenomena. This means that any scientific knowledge evolves from a mere collection of facts to a hypothesis to a law. Even among laws, there can be universal laws as well as laws applicable only to a very narrow area. Some laws can take a form of mathematical equation, which is a result of abstraction, i.e., removing any physical realities by replacing it with mathematical symbols.

At present, DTM can be found in any of these forms beginning with a mere collection or record of an individual design case. As the research in DTM proceeds, it evolves toward more abstract and general forms. While perhaps the ultimate goal of the DTM research would be to obtain a general and abstract (thus universal) theory about design, there can be theories only general but still concrete or theories abstract but individual as an intermediate state of progress. Therefore, DTM can roughly be categorized into four categories along two axes; one is "concrete vs. abstract" and the other is "individual vs. general" [133] (see Table 1):

- Concrete and Individual: By grouping records of individual design cases belonging to a specific product class and by extracting commonalities among them, we obtain "design methods" for this particular product class. For example, procedural knowledge about how to design a jet engine falls into this category but this category is not in the scope of the paper.
- Concrete and General: DTM in this category aims at concrete descriptions but applicable to a wide variety of products. This type of DTM can be obtained by generalizing design methods. This generalization is possible by focusing on particular characteristics common to different types of products. By focusing on functions, we obtain so-called prescriptive design methodologies such as Pahl and Beitz [98]. Similarly, by focusing on various concrete design goals within design, we obtain DfX (Design for X). If we focus only on design process management, we obtain process technologies to control and manage product development processes, such as concurrent engineering.
- Abstract and Individual: By abstracting design methods, we obtain this type of DTM applicable (only) to a specific class of product design. Abstraction often takes a form of mathematics, meaning design solutions can be obtained algorithmically with computation. DTM in this category includes, for example, a variety of computational methods for optimization and engineering computation. Note that these computational methods do

Table 1
DTM categorization by Tomiyama [133].

	General	Individual
Abstract	Design theory (GDT, UDT)	Math-based methods (optimization, Axiomatic Design, Taguchi Method Computer programs
Concrete	Design methodology (Adaptable Design, Characteristics-Properties Modeling of Weber, Contact and Channel Model of Albers, Emergent Synthesis, Hansen, Hubka and Eder, Integrated Product Development of Andreasen, Koller, Muller, Pahl and Beitz, Roth, TRIZ, Ullman, Ulrich and Eppinger) Methodology to achieve concrete goals (Axiomatic Design, Design for X, Design Decision-Making Methods, DSM, FMEA, QFD, Total Design of Pugh) Process methodologies (Concurrent Engineering, DSM)	Design methods

not include modeling systems (such as geometric modeling), because they are "modeling frameworks" rather than "design methods". However, some DTM methods describe design at such an abstract level that they are applicable to a certain class of design targeting specific goals (for instance, Taguchi method [127]) for quality design). Note, however, that

- Abstract and General: Design Theories about design processes, activities, and knowledge. For example, General Design Theory (GDT) by Yoshikawa [138,165,166] explains design as knowledge operations (set operations).

While design methodology deals with concrete design procedures at the process and activity level (thus sometimes called prescriptive theory [40]), it does not discuss design of a specific class of artifacts (such as jet engines, buildings, and computer software) that should be called design methods.

Design methodology begins with a design process model that can be used to develop product specifications. In all cases it is apparent that the development process is commonly regarded as a logical sequence of phases in which tasks are completed. Although differences exist in for instance the scope of the models and the use of iterations, all models show a similar way of describing a progression through a sequence of events.

3.2. Classification of finger and Dixon

In 1989, Finger and Dixon published a landmark review of DTM in mechanical engineering domain and categorized various theories and methodologies into the following six categories [40,41]:

1. Descriptive models of design processes (Descriptive): Protocol studies [149], cognitive models [44], case studies [156], and so-called German school of design methodologies (e.g., [65,98]).
2. Prescriptive models for design (Prescriptive): Canonical design process (e.g., [12,42]), morphological analysis (e.g., [98]), and prescriptive models of the design artifacts (e.g., GDT [104,138,165,166], Suh's Axiomatic Design (AD) [123,124], and Taguchi Method [127]).
3. Computer-based models of design processes (Computer-based): Parametric design, configuration design, AI-based methods for conceptual design [43,120,121], and distributed agent-based design [28].
4. Languages, representations, and environments for design (Representations): Geometric modeling, shape grammars, behavior and function modeling [150], feature-based modeling [32], product modeling [81], and integrated design support environments.
5. Analysis to support design decisions (Analysis): Optimization methods [110], interfaces to finite element analysis (or CAE), and decision-making support.
6. Design for manufacturing and other life cycle issues such as reliability, serviceability, etc. (DfX): concurrent engineering [119], design for X [62], tolerances [39,132], life cycle engineering [5], and computer-based design advisory systems.

While the survey paper by Finger and Dixon was considered complete in 1989, after 20 years obviously it needs a revision. For instance, many important theories and techniques (even available at the time), including TRIZ [6,7] and QFD (Quality Function Deployment) [92], were missing, although the authors' intention was never to be exhaustive. The categorization itself needs revision, too, particularly due to the substantial progresses of computer-related technologies made in the past 20 years.

3.3. Classification of Horváth

Another categorization was offered by Horváth [59] which aims at exhaustively covering the whole spectrum of design research. The categorization includes:

- Design philosophy,
- Design technology,
- Human assets,
- Design knowledge,
- Artifacts knowledge,
- Process knowledge,
- Design theory,
- Design methodology,
- Design applications.

While this categorization illustrates conceptual ingredients of these research results as well as their relative positions, unfortunately this review does not offer conceptual resolution that is necessary in choosing a methodology in a particular application situation.

3.4. History of design research in Germany

Design methodology study has been particularly active in Europe, among others, in German speaking countries. Fig. 1 summarizes the comprehensive research results in genealogy of the German design research community made by Heymann [57]. Some names in Fig. 1 will be mentioned in later sections.

Among these, some epoch-making achievements can be identified. In 1976, Rodenacker came up with a design methodology based on function decomposition [107]. Fig. 2 depicts the function of a machine transforming energy, material, and signal (information), which is common to the majority of design researchers including Pahl and Beitz [98]. After decomposing the required functions into subfunctions resulting in a function hierarchy, a function element that performs a unit transformation function is identified. The total solution is synthesized by assembling such function elements. To facilitate this approach,

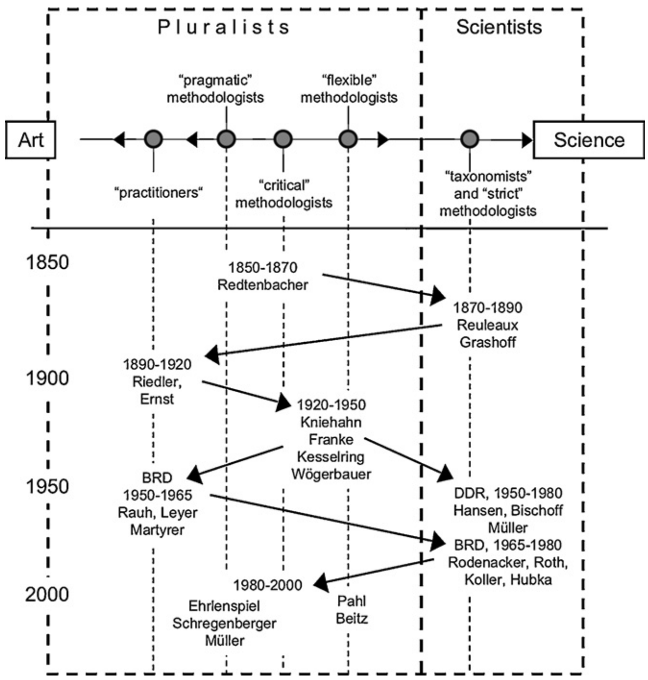

Fig. 1. German design research genealogy [57].

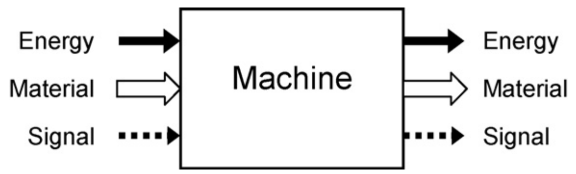

Fig. 2. Machine's function.

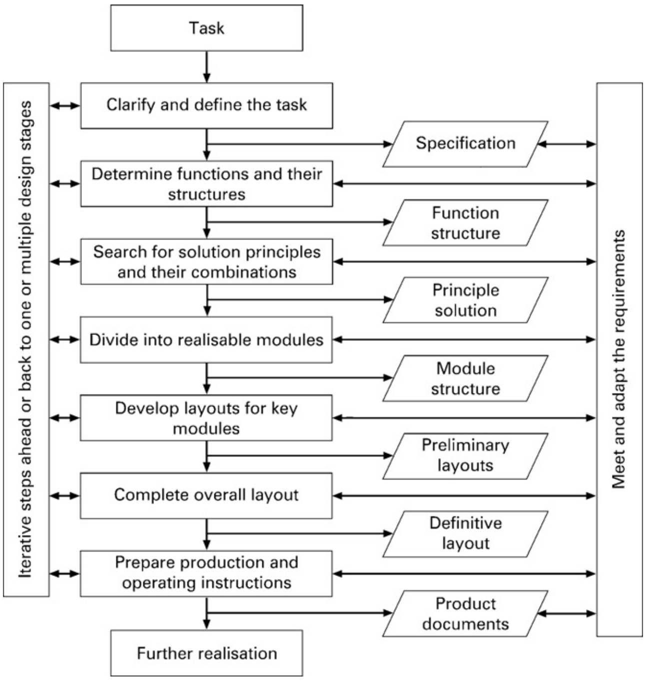

Fig. 3. Recommended design process (VDI 2221 [151]).

Rodenacker proposed to focus on physical laws and effects. His book contained a database of these function elements. This idea inspired many researchers at the time. For instance, Roth compiled a catalogue of elements classified by function [109]. Obviously, this definition of function gives limitations to the class of design that can be handled by these methodologies [150].

These ideas were particularly revolutionary to design education. Before these researchers, design education meant drawing and engineering calculations. Instead, they recognized the importance of beginning with function and insisted, in this way, more rational, innovative design could be possible in much shorter time.

It is worth mentioning that all these research efforts resulted in VDI (Association of German Engineers) recommendations 2221 [151] and 2222 [152]. VDI 2221 is about product development processes and Fig. 3 depicts its recommended design process. VDI 2222 is about conceptual design. These guidelines represent, in a way, common agreements of the researchers at the time.

4. Classification based on general design theory

In 2006, Tomiyama [134] proposed a rational classification of DTM based on Yoshikawa's GDT [104,138,165,166]. GDT is a theory of design knowledge based on axiomatic set theory. GDT inspired a number of researchers who resulted in Kakuda's Abstract Design Theory (ADT) [70] and Grabowski's Universal Design theory (UDT) [45,46] as well.

4.1. General design theory

GDT's major achievement is a mathematical formulation of design processes. GDT deals with concepts that only exist in our mental recognition. GDT tries to explain how design is conceptually performed with knowledge manipulation based on axiomatic set theory. In this sense, GDT is not a design theory but an abstract theory about (design) knowledge and its operations as well.

4.1.1. Axioms of GDT

GDT begins with a manifesto that our knowledge can be mathematically formalized and operated. This is represented by three axioms that define knowledge as topology and operations as set operations. GDT regards a design process as a mapping from the function space to the attribute space, both of which are defined over the entity concept set. Based on axiomatic set theory, we can mathematically derive interesting theorems that can well explain a design process.

GDT makes a distinction between an entity and an entity concept. An entity is a concrete existing object, and an entity concept is its abstract, mental impression conceived by a human being. (We can also say that an entity concept is an identifier.) An entity concept might be associated with its properties, such as color, size, function, and place. These properties are called abstract concepts and include attributes and functions.

GDT then continues to define its axiom as follow:

- Axiom 1 (Axiom of recognition): Any entity can be recognized or described by attributes and/or other abstract concepts.
- Axiom 2 (Axiom of correspondence): The entity set S' and the set of entity concept S have one-to-one correspondence.
- Axiom 3 (Axiom of operation): The set of abstract concept is a topology of the set of entity concept.

We assume here that there exists a set, S', that includes entities that existed in the past, exist now, and will exist in the future. This set, entity set S' or entity concept set S, represents a perfect database of knowledge about entities. Axiom 2 guarantees that S and S' are identical as well as the existence of a super designer who knows everything. (If this axiom does not exist, the designer's knowledge about entities will have defects, which is the case for realistic human designers. This means at this stage we are dealing with so-called "ideal knowledge" that is only for the purpose of thought experiment.) Axiom 3 signifies that it is possible to logically operate abstract concepts as if they were just ordinary mathematical sets. Accordingly, we can use set operations, such as intersection, union, and negation.

4.1.2. Design processes as design knowledge operations

GDT sees design as design knowledge operations, i.e., set operational processes regarding the entity set and its subsets. Fig. 4 illustrates design process in GDT's framework:

1. First the knowledge about entity must exist. For this knowledge usable, it must be categorized with abstract concepts (Fig. 4 most left).
2. The region in which a new design solution exists can be designated as a result of logical operations of abstract concepts (Fig. 4 second from the left).
3. The designer finds an entity that can fulfill these requirements designated with abstract concepts (Fig. 4 middle). If no design solution is known (this corresponds to the imperfect situation 1, i.e., vacancy in knowledge), the process becomes the core process of synthesis in design [139]. In this situation, a number of strategies can be possible (see the next section). It must be noted that Step 2 is a necessary condition for any new design, because without such conceptual combination we do not even imagine the necessity for new design.
4. If a design solution as "entity concept" is obtained, the solution is mapped from the function space to the attribute space and its neighborhood in the attribute space is analyzed to obtain attributive information necessary for production such as shape, geometry, material, etc. (Fig. 4 second from the right and most right).

Following the model depicted in Fig. 4, the following categorizes various DTM into roughly three categories, which is summarized in Table 2.

4.2. DTM to generate a new design solution

Tomiyama identified strategies that can be employed for this case, viz., creativity-based design, combination-based design, and

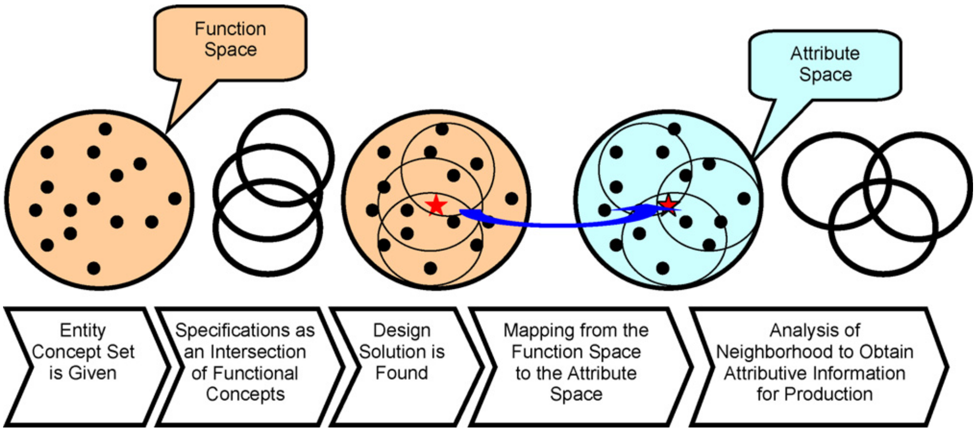

Fig. 4. Design process in ideal knowledge.

modification-based design [134]. Note that in these categorizations, one design method can be categorized in multiple categories.

4.2.1. Creativity-based design

A new design solution is generated as a new element of the entity set. This case corresponds to invention and not only an artifact but also a piece of new knowledge about this new design are indeed created. This is heavily dependent on human intuitive creativity and few theories can rationally explain it in a general framework [27]. A general formalization of this type of process with logic is abduction [22,44,54,113,137,139,167].

Abduction was first formalized by Peirce [22,54]. Deduction is a reasoning process, given proposition P and rule $P \rightarrow Q$, to derive Q using *modus ponens*. Induction is a reasoning process to derive rule $P \rightarrow Q$ from observation that whenever Q happens always P exists (but not the other way around). Abduction is a reasoning process to derive P from rule $P \rightarrow Q$ and observation Q. Suppose rule $P \rightarrow Q$ states that embodiment P realizes performance Q. Given requirement Q, one of design solutions would be P. Therefore, abduction is considered to play a major reasoning mode within design and diagnostics [137,167], although its reasoning mechanisms are not yet completely established [113].

Shah [115] points out two approaches to achieve creative designs, viz., intuitive and systematic. The former, intuitive approaches increases the flow of ideas, remove mental blocks, and increase the chances of conditions perceived to be promoters of creativity through such mental reasoning processes as association and analogy. By exposing designers to a collection of knowledge that they never experienced, it is expected that their imagination can be stimulated. Examples of such collections of knowledge could be books, archives of past designs (museums), other designers (i.e., a variety of methods for brainstorming), and some unrelated areas from which designers can be inspired (e.g., bio-inspired design).

4.2.2. Combination-based design

The latter of Shah's categorization, systematic approaches define methodologies to apply design knowledge and to arrive at creative designs more rationally and systematically. These methodologies assume one important assumption; existence of building blocks and rules to combine them to arrive at a new design solution. For example, a new machine can be designed by combining known components or units. Combinatorial logical circuit design is another example. The question here is however the level of those components. Many of German design methodologies are based on this idea and discussed in this paper.

4.2.3. Modification-based design

Modification-based design is perhaps the most often practiced method and begins with a solution close enough to the final solution. Examples of this method are parametric design and case-based reasoning. Design grammar (or shape grammar) is another approach [122]. A near solution can be modified according to some rules such as:

1. components are added ($A \rightarrow A + B$),
2. exchanged ($A + B \rightarrow A + B'$),
3. merged ($A + B \rightarrow A'$),
4. removed ($A + B \rightarrow A$).

These rules can be applied to solutions obtained by systematic methods or creativity-based design methods.

Table 2
Categorization of DTM based on GDT.

DTM categories	Examples
DTM to generate a new design solution	
Creativity-based design	Abduction
	Emergent synthesis (genetic algorithm, simulated annealing, ANN, and learning)
	Intuitive approaches (association, analogy, stimulation methods, brainstorming, bio-inspired design)
Combination-based design	Systematic approaches (Pahl and Beitz)
Modification-based design	Parametric design, Case-based reasoning, shape grammar, modification rules
	TRIZ
	Emergent synthesis
DTM to enrich functional and attributive information of design solutions	QFD, axiomatic design, FMEA
	Analysis techniques, optimization techniques
	DfX, Taguchi method, axiomatic design
	Genetic algorithm
DTM to manage design and to represent design knowledge	Design knowledge modeling, representation
	Process technologies (concurrent engineering, DSM)

4.3. DTM to enrich functional and attributive information of design solutions

Once a design solution is found in the area designated by the functional requirements, an analysis is conducted regarding its neighborhood, not only in the attribute space but also in the function space. The latter is carried out to achieve perfect design (e.g., to enhance customer satisfaction). Analyzing attributive neighborhood of a design solution and enriching attributive information are equivalent to improving performance and eventually to generating sufficient information to physically build the design solution.

4.4. DTM to manage design and to represent design knowledge

Design is a human activity largely driven by knowledge. A design process involves design knowledge and design information to be handled by a designer. This means that we need theories and methodologies to capture, represent, model, and codify design knowledge and information [16]. At the same time, these sorts of knowledge have to be used appropriately.

This requires us to study two DTM areas. One is those theories and methodologies to capture, represent, model, and codify design knowledge and information about design processes, design objects, environments, and any other life cycle issues. The other is the management of product development processes, because the scale of products is becoming increasingly bigger and the complexity of products as well as of processes is increasing rapidly. This DTM area includes those theories and methodologies to manage design, viz., design knowledge, design information, design process, resources, and design complexity.

5. Research methods

5.1. Wiki based information collection

The authors first identified topics to be included in this keynote paper. After the outline was structured, special Wiki [83] pages[1] were set up and authors and other contributors filled in the data. The system allowed them to freely add/modify entries. The pages are open to public but additions and modifications are limited to those who were given permissions to do so. The pages are intended to serve long-term educational and referential purposes.

This method has obvious advantages such as visible progress being available anytime and anywhere and relatively easy change management. On the other hand, one of the disadvantages was that it did not encourage authors and contributors to directly fill in data because it looked too complete.

5.2. Theories and methodologies investigated

As discussed in [40,41,59], design research in general is not limited to DTM. By observing industrial practices, we can also identify that a number of techniques and practices are used. However, this keynote focuses on rather pure DTM that is a primary subject in design education as well as for the space reason. Such excluded techniques are, for instance, so-called Toyota product development method [93,157] and design review which is a regular intermediate check of design results not only by the design members but also relevant stakeholders to facilitate early detection of problems as well as sharing design information [68].

Due to the focus on DTM, domain integration approaches are not taken into account here, either. A typical example is mechatronics in which mechanical engineering, electronics, control engineering, and software engineering are integrated to exhibit superior functions. In such multi-disciplinary product development, V-model of systems engineering is a widespread development approach and is used in many industrial areas [153]. Within multi-disciplinary product development, concurrent execution of different domains and resolution of conflicts and interferences among them become critical.

The recent advances of ICT (Information Communication Technology) changed the way product development is carried out. Modern product development cannot exist without various technical information systems, such as CAD (Computer Aided Design), CAE (Computer Aided Engineering), and PDM (Product Data Management). During production and later life cycle stages, it is crucial for any manufacturer to use CAM (Computer Aided Manufacturing), ERP (Enterprise Resource Planning), CRM (Customer Relation Management), and PLM (Product Lifecycle Management). All of these "digital engineering" or "virtual engineering" technologies and systems to model and represent design knowledge and to utilize it [14,15] are outside the scope of this keynote paper. Also, function modeling is an important issue relevant to design methodologies. However, one of the core issues during design and manufacturing is knowledge management [132] that has a close connection with design knowledge itself which can be a topic of DTM. This issue could not be touched, either, for the space reason.

Besides GDT, the following is the list of DTM covered in this paper in alphabetical order. Except for GDT and UDT (Universal Design Theory) by Grabowski, they all belong to "general and concrete" or "individual and abstract" categories in Table 1. These roughly overlap with theories and methodologies listed in Table 2, too:

- Adaptable Design,
- Axiomatic Design (AD),
- Characteristics-Properties Modeling (CPM) of Weber,
- Concurrent Engineering,
- Contact and Channel Model (C&CM) of Albers,
- Design for X (DfX),
- Design Decision-Making Methods,
- Design Structure Matrix (DSM),
- Emergent Synthesis,
- Failure Mode and Effect Analysis (FMEA),
- Hansen,
- Hubka and Eder,
- Integrated Product Development of Andreasen,
- Koller,
- Pahl and Beitz,
- Quality Function Deployment (QFD),
- Roth,
- Taguchi Method,
- Total Design of Pugh,
- TRIZ,
- Universal Design Theory (UDT),
- Ullman,
- Ulrich and Eppinger.

6. DTM (in alphabetical order)

6.1. Adaptable design

6.1.1. Design adaptability and product adaptability

Adaptable design [48] is a new design approach that aims at creating designs and products that can be easily adapted for different and changing requirements. When design requirements are modified due to changes in customer requirements or the operating environment of products or due to advances of technology, either the existing design needs to be adapted to create a new design and its product, or the existing product needs to be adapted directly to satisfy the new requirements. To reduce the efforts of design and product adaptation, both design and product adaptability should be considered at the design stage. Adaptable design is, therefore, a design methodology for ease of adaptation of design or product considering changes in requirements.

Design adaptability is the capability of an existing design to be adapted to create a new or modified design based on the changed

[1] http://www.opm.ctw.utwente.nl/wiki/index.php/Design_Theory_and_Methodology.

requirements. The producer can benefit from design adaptability by reusing most of the existing design solutions and production processes to shorten product development lead-time and improve product quality. Adaptable design for design adaptability is effective in the design process when a population of designs and their realizations (products) exist.

Product adaptability is the capability of a physical product to be adapted to satisfy the changed requirements. Product adaptability is usually achieved by modifying the existing product, such as adding new components and/or modules, replacing or upgrading the existing components/modules/controllers/software with new ones, and reconfiguring the existing components/modules/controllers/software.

A further distinction of product adaptability can be run-time adaptability and life-time adaptability [24]. Run-time adaptability is adaptability that can be exhibited during operation, for example, adapting to machine's conditions. Life-time adaptability is adaptability for retrofitting, upgrading, downgrading, remanufacturing, and reusing. The user can benefit from product adaptability by reusing most components/modules of the existing product rather than having to purchase a new product.

6.1.2. Benefits of adaptable design

Economical benefit: By considering design adaptability, a new design and its product can be created easier by modifying the existing design. Design adaptability also provides an opportunity to design customized products based on specific requirements of individual customers at reasonable costs.

Environmental benefit: When a product reaches the end of life, basically there are three scenarios; reuse of components in the remanufacturing process, material recycling, or discarding (ending up with landfill or incineration with or without energy recovery). While adaptable design offers of prolonging the product life itself, it also facilitates remanufacturing and recycling processes.

6.1.3. Adaptable design vs. other design approaches

Adaptable design vs. modular design: Although products developed using adaptable design may have modular architecture, products developed using the modular design approach are not necessarily adaptable and able to respond to changes in functional requirements. Modular design is often used to reduce the effort of design and manufacturing for the producers.

Adaptable design vs. product platform/family design: Platform design is an extension of modular design through the sharing of a common module – the platform – in all the designs of a product family. Although product platform and family design can better satisfy customer needs with a variety of products, customer needs in the form of changes in functional requirements of the purchased products are not addressed. Adaptable design, with platforms, can address these new functional changes effectively.

Adaptable design vs. mass customization design: Mass customization design aims at developing products based on the requirements of individual customers with near mass production efficiency [141]. Mass customization requires adaptability of products as well as sophisticated computer-based design systems and production planning/control systems.

Adaptable design vs. reconfigurable design: Reconfigurable products are considered adaptable products created to replace multiple products with a single one. However, other objectives of adaptable design, such as extension of additional functions, upgrade of modules, etc., are not considered in reconfigurable design. Adaptable design is a wider concept than reconfigurable design.

6.1.4. Key issues in adaptable design

In the past three decades, many design theories and methodologies have been developed to improve design efficiency by using design knowledge. Case-based reasoning was used to create a new design solution based on the solutions to similar past design problems [55,86]. Knowledge-based design was employed to create a new design using the knowledge achieved from past design experience [121].

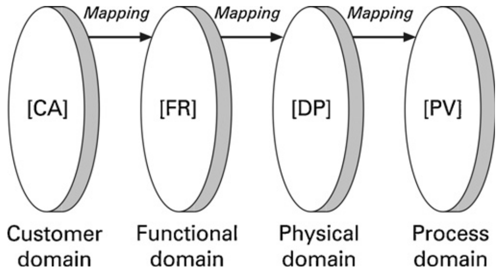

Fig. 5. Four domains in axiomatic design.

Ontologies were utilized for formalizing domain knowledge in a way to make it accessible, shareable and reusable in design [29]. Design histories and rationales were modeled to describe past experience and to help future design [103]. Design repositories were developed for modeling product information, such that artifact data were gathered, archived, distributed and used effectively in the design process [17]. A detailed review on design reuse was provided by Sivaloganathan and Shahin [118]. These design methods can help designers consider design adaptability.

6.2. Axiomatic design

Axiomatic design theory and method [123–126] have been widely reported in CIRP community. According to Google Scholar search,[2] axiomatic design under Suh's name was one of the most cited engineering design publications thus far. Axiomatic design states the best design solution fulfills two axioms [123]:
1. Maximum independence of the functional elements.
2. Minimum information content.

Compliance with the first axiom assures that designs will be adjustable, controllable and will avoid unintended consequences. Compliance with the second axiom assures that the design will be robust with a maximum probability of success. There are also theorems and corollaries associated with the axioms [123].

The discovery of the design axioms in the 1970s [123] provided the means to teach design in more scientific way. Successful experience in teaching and applying axiomatic design consists of three elements each with two parts [20]. The parts of the first element are the axioms. In order to apply the axioms systematically through the design a structure for the design elements is required. The structure is the second element and its two parts are a horizontal decomposition into domains of customer, functional, physical and process domains as shown in Fig. 5, and a vertical decomposition in a hierarchy from general to specific aspects of the design. The third element is the process. It is composed of zigzagging decomposition to create the design hierarchies in the domains from the top down by first developing the functional requirements (FRs) from the customer attributes (CAs) in the customer domain then selecting the Design Parameters (DPs) in the physical domain to satisfy the FRs and the corresponding Process Variables (PVs) in the process domain to create the DPs. The zigzagging decomposition continues from the top down through the hierarchy to the most specific level of the most elementary design features below which the solution is obvious. At each level in the decomposition the solution is tested against the axioms and constraints. The second part of the process is the integration of the elementary features into the solid model. Features can be physically integrated provided the functions they fulfill remain independent.

In order to check for compliance with Axiom 1, the independence axiom, Suh defines a design matrix ([A]) which is used to

[2] http://scholar.google.com.

display which DPs influence which FRs (Eq. (1)):

$$[FR] = [A][DP] \quad (1)$$

The desirable design is uncoupled where matrix is diagonal. If the matrix is triangular it is a decoupled design, and there is a fixed order of adjustment of the DPs to satisfy the FRs. Otherwise, the design is a coupled design which should be avoided.

Axiomatic design theory has been used in a wide range of industrial applications ranging from software design to products and manufacturing systems design [49,123,124].

Axiomatic design is not especially daunting, although it has given that impression. Axiomatic design has been successfully used with first year engineering students [130]. In comparison with algorithmic-based or procedure-based design methods, axiomatic design can appear to be more difficult to implement and teach. In the situations where axiomatic design has not been adopted in the teaching of engineering design, the insufficient training and practical experiences may be the reasons. Without good training and support axiomatic design may not appear to be as easy to follow as the more conventional, algorithmic, or systematic, methodological design methods [90]. These conventional methods lack the advantage of systematic evaluation that comes from being governed by axioms.

6.3. Characteristics-Properties Modeling of Weber

Recently Weber develops and propagates an approach called CPM/PDD; Characteristics-Properties Modeling (CPM) as the product/system modeling side and based on this, Property-Driven Development (PDD) explaining the process of developing and designing products [161–163]. The goals of the CPM/PDD approach are:

- To deliver a framework into which several existing DTM approaches fit – including ones that were so far regarded incompatible like the European schools (e.g., represented by Pahl and Beitz [98] or VDI 2221 [151]) on one hand and Suh's Axiomatic Design [123,124] on the other hand).
- To give background to and integrate methods such as DfX [162].
- To provide a new explanation what controls the product development/design process.
- To explain some still open theoretical and practical questions (e.g., how to come from general concepts of designing to application-specific procedures [163]).
- To deliver a theoretical base for the development and use of methods and tools in the development process, including CAX (e.g., CAD/CAM/CAE) [164].

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

- The characteristics (formally denoted Ci) describe 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 designer.
- The properties (P_j) describe the product's behavior (e.g., function, weight, safety and reliability, aesthetic properties, manufacturability, assemblability, environmental friendliness, cost, etc.). They cannot be directly influenced by the developer/designer.

The characteristics are very similar to what is called "internal properties" by Hubka and Eder [67] and what in Axiomatic Design is called "design parameters" (DPs) [123]. The properties as defined in the CPM/PDD approach are related to the "external properties" of Hubka and Eder and to the "functional requirements" (FRs) according to Axiomatic Design. The new part in the CPM/PDD approach is that the distinction between characteristics and properties is put into the center of reasoning about product development/design.

To be able to handle characteristics and properties – literally thousands of them in complex products – and to keep track of them in the development process they have to be structured. There are two main relations between characteristics and properties:

Analysis: Based on known/given characteristics of a product its properties are determined (its behavior is analyzed), or predicted if the product does not yet exist. Analyses can, in principle, be performed by experiments (using a physical model/mock-up, a prototype or an actual product after manufacturing) or "virtually" (by calculation and/or using digital simulation tools).

Synthesis: Based on a given, i.e. required, set of properties the product's characteristics are established and appropriate values are assigned. Synthesis is the main activity in product development/design. The requirements list is mainly seen as a list of required properties and the task of the designer is to find appropriate solutions, i.e. an appropriate set of characteristics to meet the requirements.

Against this background, product development/design is seen as an activity that consists of synthesis–analysis–evaluation cycles and which is controlled by the properties. More exactly: At any time in the process evaluating the "gap" between "Ist"-properties (as-is-properties) and "Soll"-properties (=requirements) drives the process.

During the process, in every synthesis step, increasingly more characteristics of the product are established and their values assigned; in parallel, by means of analysis, more precise information about the product's properties/behavior is generated.

In principle, there is no *a priori* preference among properties; all are seen equal and equally important. Therefore, in the CPM/PDD approach there is no strict stage model of the product development/design process, starting from function and then doing the rest. The question of which properties are relevant, how they are structured and what is the sequence of cycles of the product development/design process entirely is application-dependent and is exactly what distinguishes procedures in different branches of industry and/or companies.

6.4. Concurrent Engineering

Concurrent Engineering (CE) is an approach to product development, in which considerations about product life cycle processes, from product planning, design, production to delivery, service, and even end-of-life, are integrated to reduce product development lead time and to improve product quality. It is well known that least commitment can greatly reduce the cost of regret in later processes. The idea first appeared through the study by US researchers to analyze the competitiveness of Japanese automotive industry in the 1980s. At that time, as the report of the US National Research Council (NRC) [96] stated that product development performance of Japanese automotive industry excelled to the US industry. Fig. 6 shows a comparison of necessary lead time for developing automotive major body stamping dies.

The US-NRC report and the following well-known book [159] by an MIT-Harvard team argued that Japanese superiority came from many factors specific to Japanese industrial practice, such as tight communication between product and process development teams, target sharing by team members, front loading of potentially difficult issues, overlapped execution of processes based on

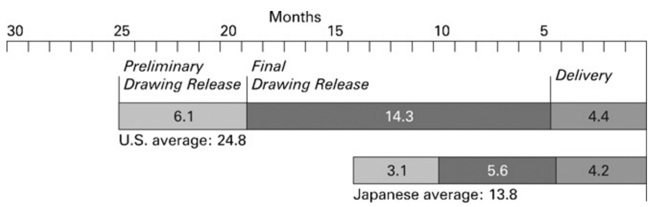

Fig. 6. Comparison of lead time for developing automotive major body stamping dies in 1980s [96].

temporarily dispatched results from the upstream processes, and so on. By such practices, Japanese companies eliminated waste of resources (Muda), and achieved efficient product development. Such practices were so natural to Japanese engineers that they did not recognize these approaches as special methods. However the MIT-Harvard team recognized their uniqueness, and named the whole Japanese approach as a Lean Production Method, which eventually had a strong influence returning on Japanese industry to reshape their processes.

CE played a central role in Lean Production. However, to its practical nature and human-dependence, it has been interpreted in many different ways [119]. Its basic way of thinking has inspired many new product design and development researches. They include the followings:

1. Sharing of design intent, manufacturing constraints, and other life cycle information.
2. Design for manufacturing, and its extension to design for X (see Section 6.6).
3. Mass customization through front-loading approach.
4. Process re-engineering through concurrent approach.
5. Negotiation and collaboration in product development [85].

A scope of CE is now naturally extended to the whole product life cycle, where product design should take into account of various life cycle constraints, such as maintenance, take-back, disassembling and recycling requirements [74]. A core of CE in such an extended environment is a method of design and associated process management. Those processes have complicated mutual dependency, which causes inefficient iterations of activities and error-prone processes. To cope with these issues, there are many researches for visualizing process dependency, and reorganizing iterative processes into streamline processes [94,147].

The essence of these approaches is to identify critical dependency of the processes, and to up-shift the independent processes as much as possible. At the same time it is very important not to make too early decisions based on uncertain information. With keywords of late decision and least commitment, a concept of set-based CE [93,157] aims to develop many interacting design options in parallel to finally settle down an optimal solution. Those methods are still not formalized and human dependent.

Recent development of digital engineering offers a firm basis for implementing sophisticated concurrent engineering idea. All the required product and process information is represented in digital data/knowledge base, and utilized for product design in an integrated manner. Various kinds of IT tools are now available to support concurrent engineering processes [101].

Although implicit, CE is a well-developed product development approach implemented in various industries, particularly in automotive industry worldwide. From the organizational viewpoint, in combination with the idea of Chief Engineer system, CE made great successes in innovative product developments, such as hybrid cars. From the research viewpoint, CE is still in the stage of practice, and needs more systematization efforts also taking into account the interaction behavior of the different stakeholders, although many digital and virtual engineering tools based on advanced IT are available [14,15,75,88,99].

6.5. Contact and Channel Model (C&CM) of Albers

The model building blocks of the Contact and Channel Model (C&CM) are Working Surface Pairs (WSP) and Channel and Support Structures (CSS) [4]. This theory has been developed and taught by Albers at the Karlsruhe Institute of Technology (KIT) and applied to a number of design cases since 2002 [1–3].

The motivation to develop C&CM stems from the observation of students and engineers in industry who struggle while analyzing concrete products in abstract terms as well as linking an abstract model, such as a functional model, to a part of the product. The notion of the C&CM builds on earlier work of, e.g., Rodenacker [107], Roth [108], Koller [80] and Hubka [66], but adds important insights about the relations between the basic elements of technical systems. Already Rodenacker used similar terms of *Working Surface* and *Working Space* and states that these notions are applicable to all areas of engineering [107]. Roth also used these elements to bridge the gap between functional product representations and geometric product models [108]. Such earlier work aimed at automating engineering design whereas C&CM has been developed as a tool to support the problem solving processes of designers in their everyday activities.

The building blocks of C&CM allow a designer to establish an integrated model, where technical functions, shape as well as the environment in which the system should perform are represented coherently. Since decomposition of complex technical systems is not always unique [12], designers create different descriptions of the system. C&CM can deliver a coherent explanation of the technical problem so that all involved designers can work on finding an appropriate solution in a target-oriented manner. Through the creation of a problem-adjusted representation, the success of the design process becomes more secure.

6.5.1. Basic principle of C&CM

The basis principle of C&CM is exemplified by the intrusion of a self-penetrating screw. The "establishing a connection between gypsum and metal plate" can only be fulfilled quickly and reliably if (i) Working Surface Pair I between metal plate and screw tip, (ii) Working Surface Pair II between screw and bit, and (iii) Channel and Support Structure 1/2 do exist. The Channel and Support Structure (CSS) connects the Working Surface Pairs (WSP) and thus is determined through the body of the screw (Fig. 7). If anybody tries to intrude the screw by hand, Working Surface Pair II is not established correctly, thus the function cannot be fulfilled quickly or reliably. The C&CM descriptions can be applied to any level of detail in the same way. The CSS 1/2 of the screw can be split up in further WSP and CSS in order to describe the functions in more detail (Fig. 8). Thus the same kind of model for reasoning about a design problem can be applied on any level of detail.

6.5.2. Product development with C&CM

Suppose a team of designers is given a task to create a new screw with the goal of "high intrusion reliability and shorter intrusion time". The first step is sound problem statement that explains why current screws work unsatisfactorily. Which effect prevents the quick and reliable intrusion? (Which WSP do exist?) Which functions occur? (How are WSP and CSS coherent?) Which functions are dominant for the quality of the function, thus do contribute most to the quick and reliable intrusion? For instance, is "center punching of the metal plate" a dominant function? Are other functions fulfilled?

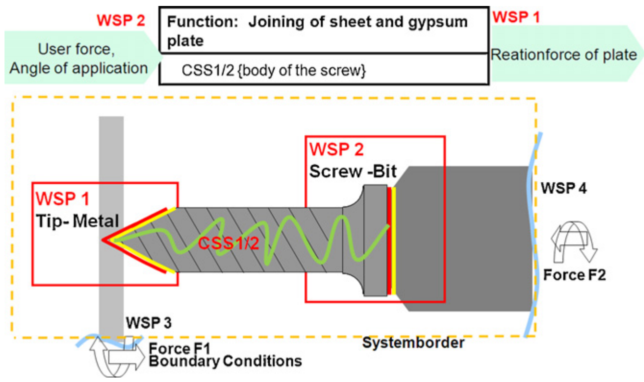

Fig. 7. Self-penetrating screw.

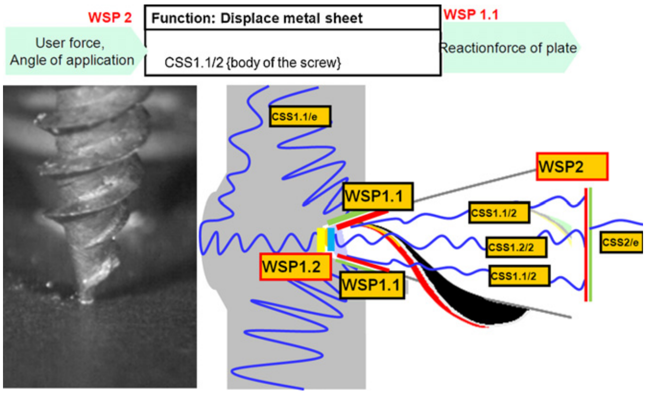

Fig. 8. The function at the tip.

The determination of WSP and CSS that characterizes the intrusion behavior is the first task of the team. To find solutions, the complex system must be explained in such a depth that all reasonable influences on the intrusion of the screw are examined, so that the team has a common understanding of the design problem. This dynamic procedure of creating a clear and causal understanding is supported strongly by C&CM.

Thus the model establishes a consensus underneath the designers, which is proven by concrete facts of WSP and CSS. The model building process ends, if the description of the problem seems to be detailed enough. The step of analysis establishes the basis for the creation of a new innovative screw. With the explicit description of the emerging WSP and CSS and their explanation in functions the know-how becomes applicable for increased requirements of a similar application of connecting two metal sheets. Principally the functions can be transferred to the new requirements. The task of the team of designers is then to adjust the properties of WSP and CSS according to the newly intended quality of the function. This means that the designers have to find out which geometric features (e.g., height and shape of the screw windings) are suited best for the new application, they have to determine materials, hardening properties and production processes, which still is truly hard development work. In contrast, with C&CM the process is structured. The process does not depend on speculation on the problem, as there is a common sense of the determined problem. Result of this process is a solution with a never unprecedented quality in function. The example shows that the application of the C&CM is successful. Yet the process of finding new solutions is often unstructured and determined by "muddling through". Current research on the use of C&CM in design processes focuses on the elicitation of model building patterns for a successful application.

6.6. *Design for X*

"Design for X" (DfX) is a generic name for the members of a family of methodologies adopted to improve design product as well as design process from a particular perspective which is represented by X [62]. According to Tichem [131], a number of different interpretations of X exist. The X-either represents:

- A specific property (e.g., cost, quality, lead time, efficiency, flexibility, risk or environmental effects).
- A life-cycle phase of the product (e.g., parts manufacturing, assembly, distribution, service or discarding) or one of the subprocesses (e.g., gripping or feeding).

Of these, manufacturability and assemblability were among the first that were considered, since both were highly apparent cost reduction drivers.

DfM (Design for Manufacturability) aims at optimized manufacturability of the product. DfM focuses on two steps in design: selection of a manufacturing process chain for a part and optimized part design for the chosen process chain. In both steps, two aspects are investigated: compatibility between a part's design and its process chain and optimization of one or more aspects like cost, flexibility, environmental harm etc. DfM affects both the product structure level and the single part level. DfA (Design for Assemblability) aims to minimize the effort of assembly of a product. The two main rules of DfA are reduction of the number of assembly operations and the amount of equipment and design of parts for easy feeding, grasping and insertion. DfA affects both the product structure level and the part and connection level of the product.

Boothroyd has assessed possible trade-offs between assembly and manufacturing costs [18]. Equipment set up times are considered in their work and are included in their cost models. These data are treated as constants in the calculations they undertake, where they fail to accurately determine differences in changeover times between various processes. In reality changeover times are strongly dependent on the product range and the manufacturing processes used.

Boothroyd recognizes the following advantages for applying DFMA (Design for Manufacturability and Assembly) (see Fig. 9):

- DFMA works systematic, due to the procedure simpler and more reliable products are developed which are less expensive to assemble and manufacture.
- DFMA encourages dialogue betweens designers and the manufacturing engineers and any other individuals who play a part in determining final product costs during the early stages of design. The benefits of simultaneous (concurrent) engineering can be achieved.
- Savings in manufacturing costs.

6.7. *Design decision-making methods*

Since the 1960s, the design decision-making has been described as an iterative process as opposed to an event. This was first proposed by the Nobel Prize winner, Herbert Simon. Fig. 10 shows his proposal of this iterative process [117].

Design decision-making, in a broad sense, involves generating design alternatives, composing an evaluation scheme to analyze the alternatives, and eventually selecting a most desirable design alternative.

Any decision process involves three fundamental phases:

- Setting the goal or objectives – if they are more than one.
- Identification of constraints.
- Identification of options.

The design for purpose, or DfX, intends to focus on the decision-making process through the identification of the goal of the design. So for example, Design for Availability implies that the goal of the

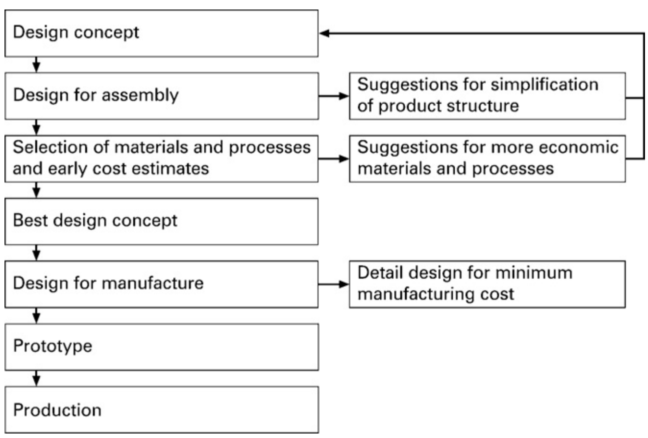

Fig. 9. DFMA process [18].

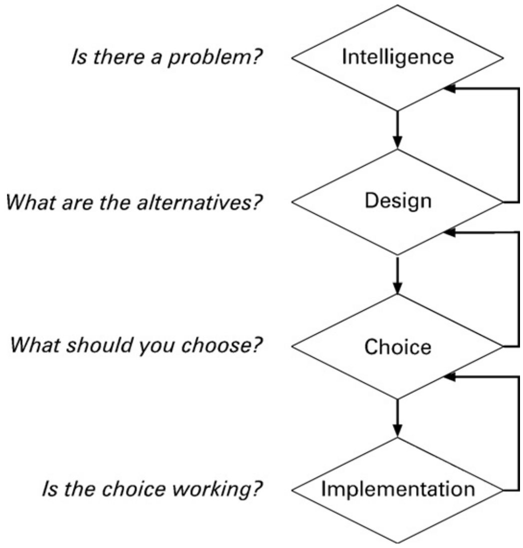

Fig. 10. The decision process by Simon [117].

design process is to ensure that the designed artifact is always available, as a goal. Now this can then be transformed into objectives such as maximization of reliability – measured by Mean Time Between Failures (MTBF), and minimization of maintainability – measured by Mean Time to Repair (MTTR). This helps to focus the design process and identify the measures by which the final design is being evaluated [97].

The research on design decision-making methods usually assumes that generating design alternatives is less an issue, rather the key problem of design is how to choose among given design alternatives. In order to make desired choices, designers must know what they want to achieve (i.e., having clearly defined design objectives) and be able to evaluate or predict the performance measures of the alternatives against what they want and in face of uncertainty. Indeed, having clear design objectives and goals is not only necessary for choosing desired designs but also important for enhancing designers' capability of generating new and more relevant design alternatives [71,123].

We can categorize design decision methods into heuristics based decision methods and decision theoretic methods. In addition, these design decision support methods, in contrast to the following decision theory details, rely on either general principles or heuristics. For instance, DfX enhances design decisions by focusing on specific desired design and bringing them into design decision-making at the early stages of design (see Section 6.6).

Although meaningful and purposeful design criteria together with well organized design processes generally can improve design results, there is little theoretical guarantee that these criteria are all consistent with what a designer wants and that the design result will be the best that the designer can achieve, especially when uncertainty is involved. Following the decision theory and decision analysis methods [60,72], design researchers to date have addressed these two issues by developing methods to acquire designers' utility functions that more reflect what designers want and decision theoretic processes that allow more consistent design evaluation throughout the design process. Design decisions are often associated with uncertainty where outcomes of a given alternative cannot be clearly specified. The utility theory provides a rigorous method for evaluating the outcomes based on decision maker's judgment on probabilities of possible consequences, and his/her attitude toward the risks that the consequences might bring.

Given the utility theory, two major questions remain: how to identify and define the utility function for a given decision maker, and how to assign probability values to the identified chance forks so that the expected utility value can be calculated. The first question relates to preference analysis, and the second one to uncertainty analysis. Researchers have developed and tested various methods including lottery based methods for identifying designers utility functions that take into consideration designers' attitude toward risks [129,158]. Various methods including imprecision methods have been proposed to address the issues involved in early stages of design where specific values of given design parameters cannot be determined [11] and to deal with uncertainties of information [13,84,87]. Viewing engineering design as a decision-making process for maximizing a company's profit has led to another axiomatic framework of design [56] that follows von Neumann and Morgenstern's assumptions [95], emphasizes the product demand based single criterion evaluation [160], and somehow oversimplifies the contents of design. Design decision-making has also been associated with design optimization where making the best choice in a complex design space is the key [19,91] and collaborative design where integrating values and information among multidisciplinary participants determines the final design results [69].

6.8. DSM

The Design Structure Matrix (DSM) (also referred to as Dependency Structure Method, Dependency Structure Matrix, Problem Solving Matrix (PSM), Incidence Matrix, *N*-square Matrix or Design Precedence Matrix) is an approach to managing complexity by focusing on information flow and interdependencies within and between different domains (e.g., spatial, energy, information, and material domains). DSM is widely used for many purposes; for example, as a tool for structuring and clustering product's components. The concept of DSM has been discussed by Browning [21]. The concept of DSM as a modularization method has been described by Pimmler and Eppinger [100].

In general, DSM is a matrix representation of, for example, a product. DSM' elements denote individual components of that product and off-diagonal numbers (or marks) represent interactions between the components. With help of clustering algorithms, it is possible to identify modules using the information stored in the DSM. Fig. 11 shows the concept of the DSM for an imaginary product, which consists of seven components (A–G) before clustering (left) and after clustering (right).

DSM analysis gives an insight into the way products or projects can be managed, by highlighting information flows, task sequences, and iteration. Moreover, DSM analysis can also be used to manage the effects of change by giving a possibility of quick identification of all processes which had been dependent on that change. Therefore, industries often see DSM as a valuable tool for designing complex systems, optimizing product architectures and technical systems. Dong et al. also pointed out that DSM is relevant to Axiomatic Design [33].

Currently, there are a number of computer software applications that make use of the DSM available on the market. Those applications are often used in aerospace, defense, semiconductor, automotive, photographic, telecom, small-scale manufacturing,

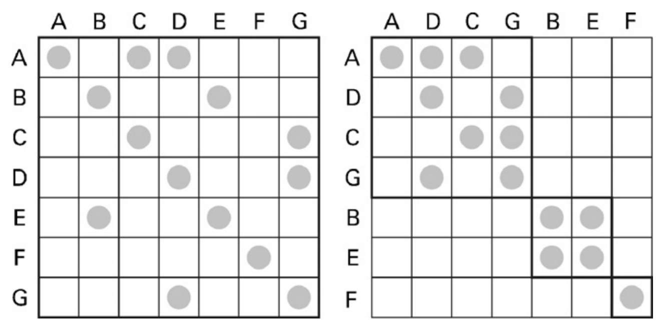

Fig. 11. An example of the DSM for an imaginary product, which consists of seven components (A–G) before clustering (left) and after clustering (right).

factory equipment, electronics, and construction projects as well as for managing software architecture. Building DSM of a product is, however, time consuming, and requires detailed product knowledge from different specialists.

Although the use of DSM increased greatly in both research and industrial practice in 1990s, the DSM approach has not yet found its place in the curriculum at the Universities. Nevertheless, there are conferences (e.g., DSM conference[3]), workshops, courses, and homepages dedicated only to DSM.[4]

6.9. Emergent synthesis

Emergent synthesis [142–146] draws a way of outlook on handling complex artifactual systems, where the local interactions between the artifacts of the system form the global behavior through bottom-up development to achieve the purpose of the whole system. The emerging global order of the system structure can be modified by rendering the global purpose to the artifacts top-down. Thus emergence related approaches are developed with both bottom-up and top-down features offering efficient, robust and adaptive solutions to the problem of synthesis. Taking into account the local and global goals, the artifacts have to build up their emerging behavior resulting in the global order of the system. Behavior of the artifacts formed depends on the designer's specification and creativity.

Emergent synthesis often uses soft-computing methods such as genetic algorithms [58], artificial neural networks (ANN) [30], simulated annealing [76], and various learning algorithms (e.g., [116]).

Emergent synthesis introduces three types of classes and their possible emergence related approaches to describe whether completeness of information could be achieved in the description of the environment and in the specification of the purpose of the artifactual system.

6.9.1. Class I type problems

In Class I type problems the description of environment and specification is complete and the problem is completely described. However, in most cases there are too many candidates of feasible solutions due to combinatorial explosion. For this type of problems evolutionary computation methods, such as genetic algorithms, genetic programming, evolutionary strategies, evolutionary programming have been successfully applied.

6.9.2. Class II type problems

In Class II the description of the environment is incomplete and the specification is complete. The problem is to cope with the dynamic properties of the unknown environment. To deal with this problem, it is required to determine the constraint information through being in interaction with the environment. Learning and adaptation based approaches such as reinforcement learning, adaptive behavior based methods are feasible to this class of problems.

6.9.3. Class III type problems

In Class III not only the environmental description but also the specification is incomplete. Besides ascertaining the dynamic environmental constraints, this class has to cope with the iterative determination of the system structure. Further emergent properties such as interactivity, self-coordination, co-evolution, and self-reference are essential.

6.10. FMEA

It is important to avoid any product failures for safety and resource efficiency reasons. It is strongly desired to identify and eliminate potential failures during product design processes and before product delivery to customers. FMEA (Failure Mode and Effect Analysis) is a systematic approach for coping with such failure problems, and was developed in the 1960s in the US aerospace industry [89]. When the criticality analysis of potential failures is stressed, it is called as FMECA (Failure Mode, Effect and Criticality Analysis).

FMEA is normally performed by a team of experts who have deep understanding of target products and production processes, and have enough training/experiences/know-how for FMEA execution. Still it is a very tedious work to perform a whole process of FMEA. Therefore applications of FMEA were limited to rather complicated large products/systems. In recent years, through the use of simple computer support tools and standardization of the method, FMEA has been spread into various industries, such as automotive and electronics industries.

Another well-known approach to failure analysis is FTA (Fault Tree Analysis) [155]. FTA is a top-down analytical approach, where, starting from a critical failure, possible failure phenomena are traced back to primitive failure causes. This is primarily failure diagnosis after product design. On the other hand, FMEA is a bottom-up synthetic approach, where primitive failure modes are identified, and possible product failures are predicted with criticality measures. Failure mode means possible changes of behavior of product primitive components or functions, which may cause critical product failures. With a comprehensive database of failure modes derived from the past failure reports and human expertise, it is possible to enumerate potential critical failures, and to improve product design during product development process. FMEA is incorporated as one of the core methods in the reliability-centered design approach.

Standard procedure of FMEA is as follows:

1. Understanding and modeling of target products and processes.
2. Identification of possible failure modes.
3. Derivation of possible product failure due to each failure mode.
4. Calculation of criticality measure of each failure mode based on failure mode occurrence, severity of the product failure and detectability of failure mode.
5. Improve the product design based on criticality measure.

FMEA has a long history of industrial applications, but it is still a human-dependent and informal method. It is not straightforward to model target products and processes in an appropriate abstraction level, and to utilize a CAD approach. Tracing the effects from failure modes to product functions requires some expertise and know-how. New approaches, such as a scenario-based approach, are proposed, but still there remain many issues. Feasible calculation of criticality measure with available data is another problem. In the future, it is expected to be integrated with computer aided total product development systems.

6.11. Hansen

Friedrich Hansen can be regarded as one of the most prominent (and also very early) representatives of the former East German school of Design Theory and Methodology. His professional background was optical and precision engineering.

In 1953 Werner Bischoff, Artur Bock and Friedrich Hansen together came from the Zeiss company in Jena to the Technical Highschool in Ilmenau (today Ilmenau University of Technology). Bischoff, Bock and Hansen had earlier set up a new work group at the Zeiss company with the task of establishing new ways to make development and design processes more effective and efficient in order to compensate for the shortage of designers which was caused by the loss of experts to the USA and the Soviet Union after World War II.

These ideas were the core of the "Ilmenau School of Engineering Design". While Bischoff concentrated on Precision Engineering and Bock on Mechanism Design, Hansen became the expert for

[3] http://www.dsm-conference.org/.
[4] http://www.dsmweb.org/.

"Systematic Design" (in German: Konstruktionssystematik) as Design Methodology was called at that time.

Hansen's first publications on Design Methodology date back to 1953. A first small booklet on "Konstruktionssystematik" was published in 1955 [51], very much aiming at engineering practice rather than academia. A more comprehensive (and also clearly more science-related) book of the same title was published in 1966 [52].

These early publications primarily covered the design process. There is no original graphical representation of Hansen's process approach (it was all explained in text and tables). The process was, however, already structured into the now well-known stages of:

- Task clarification.
- Reasoning on functions and working principles.
- Layout and detail design.

As an additional stage Hansen strongly stressed failure analysis (in German: Fehlerkritik) as an important base to optimize solutions (new as well as existing solutions). For all stages Hansen provided methods, examples, formalizations and forms, etc.

In 1974 Hansen presented a much more theoretical book titled "Konstruktionswissenschaft" ("Design Science") [53]. This book added new concepts on the objects being designed and their properties (which we would today call a "Theory of Technical Systems"). In this work Hansen defines a system as a clearly delimited part of reality which has:

- relations to its environment (in German: Umwelt, U),
- a structure (S) and
- a function (F).

"There is a meaningful relation between these three system properties. Always the function is determined by the structure and depending on the environment" [53].

The properties of a system (vector P) can be formally expressed by the following equation:

$$P = \{U, F, S\} \quad (2)$$

Based on that, Hansen distinguishes technical from other systems by defining and describing environments (U), structures (S) and functions (F) specific for them. Core issue for engineering design is the relations between function and structure, more exactly the sets of functions and the sets of structures. These are explained formally in Eqs. (3) and (4) in which a double arrow denotes a multivalent mapping:

$$\text{Analysis}: \quad S \rightarrow F \quad (3)$$

$$\text{Synthesis}: \quad F \Rightarrow S \quad (4)$$

In 1967 Hansen invited, among others, Hubka and Eder to Ilmenau to attend a workshop on Engineering Design Theory and Methodology, held during the 12th International Scientific Colloquium (a conference series which exists to this day). This event could have been the first time where researchers of the field met and discussed on an international level (East Germany, CSSR, UK).

Hansen's work was extremely influential on the further development of Design Theory and Methodology in both East and West Germany. It also had considerable political impacts: The government of East Germany saw systematic design as a means to gain technical and economic supremacy and in the 1960s and early 1970s forced Eastern German companies to apply respective procedures and methods.

6.12. Hubka and Eder

Vladimir Hubka was in the 1950s and 1960s a designer in the Czechoslovak Socialist Republic (CSSR) with a professional background in heavy machinery. In 1968 while he was visiting Denmark Technical University hosted by Andreasen, Warsaw Pact troops invaded his home country, which made him decide to stay in the West. A couple of years later, Hubka moved to the Swiss Federal University of Technology (ETH) in Zürich where he stayed until the end of his professional life.

Hubka's publications on Engineering Design took off in the early 1970s, in the beginning mostly in the German language. He certainly was one of the first authors who developed an elaborated theory which is – quite uniquely – split up into a Theory of Technical Systems [63] and a Theory of Design Processes [64,65] which are, however, closely related.

Hubka met Ernst W. Eder for the first time in 1967 during the 12th International Scientific Colloquium in Ilmenau, organized by Hansen. Eder, a born Austrian, at that time living in the UK, had written earlier articles and books on Engineering Design [34] as well as several chapters in Gregory's well-known book [47]. Much later – after Hubka's emigration to Denmark and later Switzerland – Hubka and Eder started an extremely fruitful scientific cooperation. Together they published a book on Design Science, first in German [66], later in English [67]. In a much simplified overview, this Design Science of Hubka and Eder consists of:

1. Considerations on the objects being designed and their properties (Theory of Technical Systems, TTS).
2. Statements and recommendations about the process of and useful operations in designing (design methodology, design process).
3. A concept of how to structure of design-related knowledge.

The core of the Hubka and Eder approach to TTS has the following constituents:

- A general transformation process model which serves to define the purpose and tasks of the technical system to be or being designed, and which is adaptable to the different life-phases of the system.
- A model which refers to the kinds of structures of the technical system as they are successively established according to the stages of the design process (purpose, internal process, functions, organs, components).
- A structure of (system) properties which define and describe a technical product or system after it has been designed.

The engineering design process model of Hubka and Eder roughly follows the now well-known stages of task clarification, functional reasoning, finding working principles, layout and detail design. In the stage of working principles, Hubka and Eder strongly put the concept of function carriers into the foreground which they call "organs". One organ is usually realized by portions of several physical components of the technical system.

6.13. Integrated product development of Andreasen

The danger of some of design methodologies is that they might deteriorate into prescribing "scripts" for the development phase instead of offering a framework for the guidance of the processes in this phase. Andreasen at Denmark Technical University recognized this problem [8–10], and made a distinction between the transition of phases in product development and the processes that are required. In the so-called integrated product development model (Fig. 12), the processes are related to three different aspects; market, product and production. The development cycle consists of the following phases (corresponding to the columns in Fig. 12):

- Recognition of the need.
- Investigation of the need: The output of this phase is the – basically defined – perceived need, established by a product type and process type.
- Product principle: This phase clarifies the product's use and its general principles. From this, the possible types of production and the relation to competing products are determined.

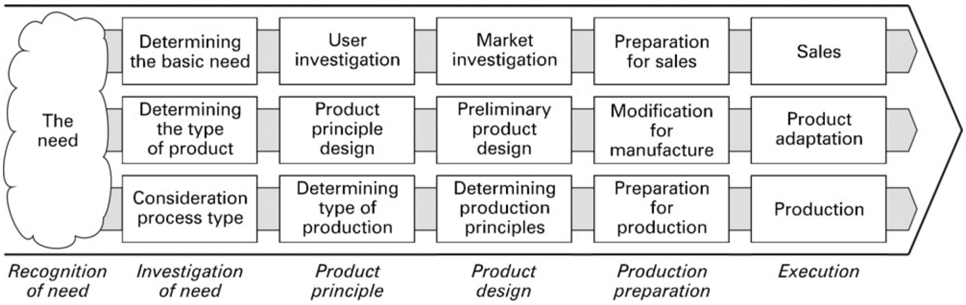

Fig. 12. Integrated product development process according to Andreasen and Hein [9].

- Product design: This phase demonstrates the feasibility of the product, the production processes and the position in the market.
- Production preparation; in this phase, the interconnection between the product, the production process and the sales system (market) is tightened.
- Execution phase: The decisive proof: production and sales.

It is obvious that the way in which the processes and the progress in the development cycle are dealt with, indicates that – although developed from strongly different backgrounds – the principles of integrated product development and concurrent engineering show considerable resemblance.

6.14. Koller

Koller belongs to the early generation of West German researchers who put engineering design on a scientific base. His professional background was precision engineering. The first edition of his book on engineering design methodology dates in 1976 [77]. The book was continuously revised [78,79] and extended and had its fourth and last edition in 1998 [80].

In the preface to his book he calls his approach "a physically and algorithmically oriented design method". Of all authors in his generation he can be regarded as the one most closely related to physical effects as an important source of innovation.

A comprehensive model of the development cycle is shown in Fig. 13 in the 1985 version [78]. It presents a product development model by defining phases, the tasks within these phases, the types of activities that are performed and some of the decisions involved. The model is in accordance with the now well-known stages of task clarification, functional reasoning, finding working principles (in Koller's terminology "[physical] effects"), layout and detail design.

Based on the idea of processing flows of energy, material and signals (information) Koller developed a fixed set of so-called basic operations for each of these cases. Koller's approach is well known for the extensive collections of physical effects (later called "catalogues of solution principles"), sorted by selected types of basic operations and required input/output combinations.

Another area where Koller's approach has notable extensions compared to other authors is the systematic variation of concepts and layouts.

Finally, Koller was in the 1970s deeply involved also in the development of CAD software, always linking tool development closely to design methodology.

6.15. Pahl and Beitz

The design method proposed by Pahl and Beitz, first published in German in 1977 and in English in 1984, is perhaps by far the most known and used one in both industry and education [98]. It has been serving also as a reference. It is based on an elaborate analysis of the fundamentals of technical systems, the fundamentals of systematic approach and general problems solving processes. The aim of the model is to adapt general statements to the requirements of the mechanical engineering design process and to incorporate the specific working and decision-making steps.

The method places design as a central activity of the whole product life cycle as shown in Fig. 14 and recognizes the repetitive nature of design. The design (or product development) process itself is decomposed further into four main phases (Fig. 15):

- Planning and clarification of the tasks; this phase specifies the information that is required. Planning refers to product planning, and clarification of the task collects information about the requirements that have to be fulfilled and about the accompanying constraints and their importance.
- Conceptual design: The aim is to determine the solution principle, achieved by abstracting the essential problems, establishing function structures, searching suitable working principles and then combining these principles in a working structure. Often a more concrete representation is required for the assessment of the structure.
- Embodiment design: Starting from the concept, the construction structure (overall layout) is constructed. Several preliminary layouts are often developed to allow for comparison of alternatives. The definite layout provides a check of function, strength, spatial compatibility and financial viability.
- Detail design: The arrangement, forms, dimensions and surface properties of all the individual parts are laid down, the materials

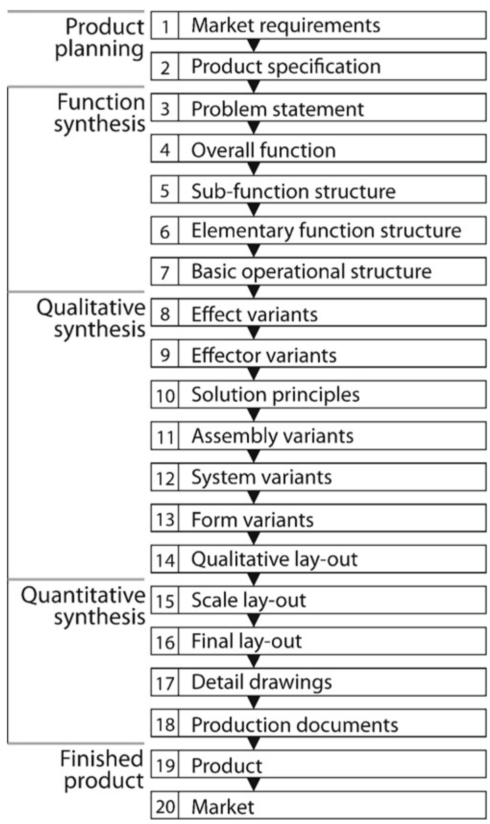

Fig. 13. Koller's design process model [78].

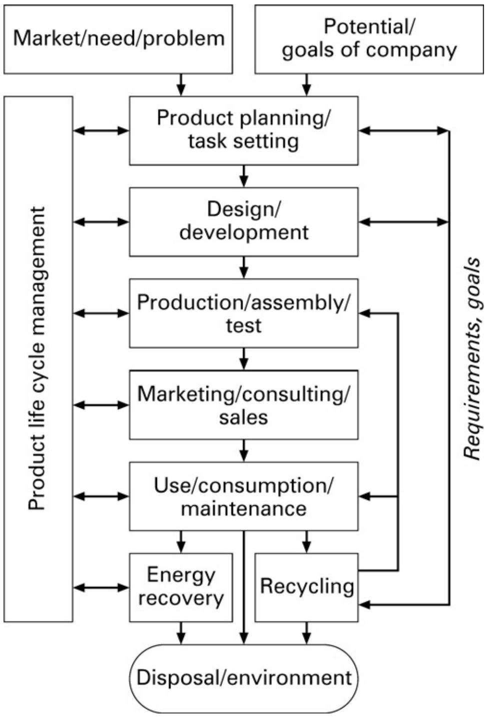

Fig. 14. Life cycle of a product of Pahl and Beitz [98].

are specified, production possibilities assessed, costs estimated and all drawings and production documents are produced. The result of the detail design phase is the specification of production.

As is the case with many of German design methodology varieties, Pahl and Beitz assume function decomposition based on the transformational function definition. Pahl and Beitz recommend to use catalogue type knowledge about physical effects to find out function elements that perform subfunctions and to combine them systematically using so-called morphological table which potentially results in a huge number of alternative solutions. They proposed a technique to reduce possible combinations and to select suitable solution variants, which is characterized by the activities "eliminate" and "prefer". However it is stated that this will not guarantee avoiding wrong decisions. The identified combinations will be then compared against requirements and evaluated using, for instance, the value engineering method.

The Pahl and Beitz method is perhaps the most taught, if not standard in engineering design courses at many educational institutes. It strongly influenced on the definition of the guideline VDI 2221 [151], too. However, it contains potential drawbacks since the method can be misused easily. For example, very often students use morphological table as justification for their intuitive design. The textbook emphasizes the importance of "task analysis" but in practice students cannot perform it sufficiently. The textbook is easy to understand, so they underestimate the difficulty and potential pitfalls in using the method. Because of these, when students go to industry, they do not use the method in practice. The value of the method seems to be understood only by experienced designers who know the correct use of the method.

6.16. QFD

In recent years, due to high demands from customers and rapid technological advances, product development becomes very complicated, and it is very difficult to maintain initial customer requirements throughout the product development life cycle. Basically it is mandatory to control manufacturing product quality according to required product design quality. For this purpose, QFD

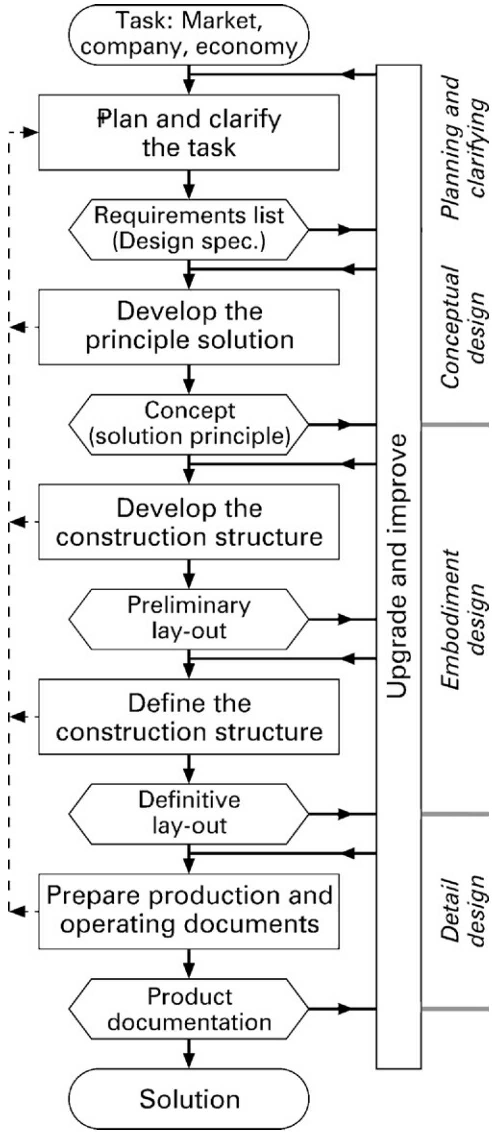

Fig. 15. Product development process of Pahl and Beitz [98].

(Quality Function Deployment) was first developed by Mizuno and Akao in the 1960s in Japan [92].

QFD has been developed over past 40 years through industrial practices, and has been interpreted in different ways. QFD was originally defined as a step-wise procedure to systematically deploy product development processes or functions which contribute to the required product quality. However, many of the industrial applications of QFD focus on the first step of the deployment which maps product functional requirements (VOC: Voice of Customers) into product structure and product components. In this case, it is called as QD (Quality Deployment).

It requires a lot of work load to perform comprehensively a whole QFD process, but its effect has been recognized by many industrial applications, particularly automotive industry where it is very important to capture customer requirements in the beginning of the long range product development. For reducing the required work load, the QFD processes have been standardized and standard templates are prepared. The benefits of QFD recognized by industrial applications are rational set up of required product quality, transfer of product quality requirements to downstream processes, avoidance of quality problems, easy comparison with competitors' products, accumulation of vast amount of product quality information, etc.

Practical steps of QFD process may be different, depending on the types of products, such as improvements of existing products, innovative new products, mass production products, order-made products, etc. Basically each step consists of mapping of quality items into other quality items by using matrix formulation (called House of Quality). Standardized steps are summarized as follows:

1. Quality Deployment: Mapping of VOC into measurable product quality characteristics, product structure and then product components.
2. Technology Deployment: Mapping of product structure and components into technology items and manufacturing processes.
3. Cost Deployment: Enumeration of cost items according to technology deployment.
4. Reliability Deployment: FMEA (Failure Mode and Effect Analysis) based on the results of the previous three steps.

For characterizing various QFD applications, the following QFD categories are advocated by the QFD committee of the Union of Japanese Scientists and Engineers:

1. Quality Assurance QFD: Traditional QD.
2. Job Function QFD: Full scale QFD.
3. TTQFD: Application of Taguchi Method (see Section 6.18) and TRIZ (see Section 6.20) for configuring mapping matrix from quality requirements to process characteristics.
4. Statistical QFD: Application of statistical methods and design of experiment for identifying quality characteristics.
5. Blue-Ocean Strategy QFD: Application of concept mining and other methods for analyzing VOC.
6. Real-time Database QFD: Construction of real-time database for QFD-related information.
7. Sustainable Growth QFD: Application of QFD methods to whole product life cycle design.

Application of QFD methods to environmentally conscious design or EcoDesign is called as QFDE (QFD for Environment), where environmental requirements are considered in addition to the normal VOC, and the rest of the steps are almost the same as the normal QFD.

6.17. Roth

Roth's model of the design process (Fig. 16) explicitly refers to design tasks, and excludes those steps that occur after the completion of the design, although, the structure of the model is suitable for the entire development phase [108]. The model shows the phases or stages in the evolution of a product design, and then breaks down these phases into activities to be executed during these phases. Iteration in this model is possible at the end of the conceptual (i.e. functional) and detailed (form design) phases, with the potential to return to any of the previous activities, once the evaluation activity (rhombus) has been performed.

Roth has become well known for his extensive work on design catalogues that collects useful function elements [109]. This resulted from his early work on algorithmic design method and was obviously inspired by such researchers of the time as Koller, Rodenacker, and Hubka.

His design process model defines four different phases and starts with a given task:

- During the Task formulation phase the task will be specified by defining and specifying functions.
- In the Functional phase the product will be developed into several concepts by determining different product functions, the phase ends by comparing the concept functions with the specified functions from the first phase. If needed iteration to any previous step is possible at this level. During this and the next stage, the design catalogue should be consulted.
- In the Form design phase the functional product concept will be detailed by defining form, materials, production methods and costs. After this detailing the developed product's properties will be compared to its functional requirements defined in the first phase.
- In the result phase the designed product will be prepared for manufacturing by creating production drawings so the product can be manufactured.

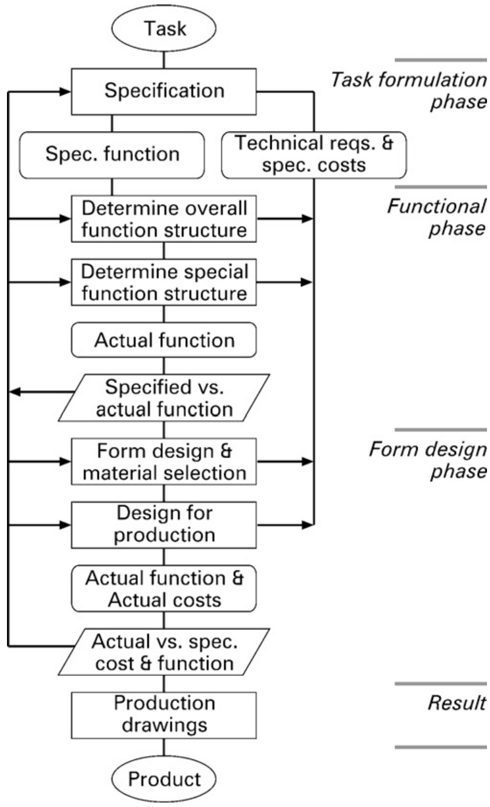

Fig. 16. Design process model of Roth [108].

6.18. Taguchi method

Taguchi Method[5] [127] aims at improving product and process quality throughout the whole product life cycle, and is considered to be a very unique and successful approach in quality engineering. The method was first proposed by Gen'ichi Taguchi, Japan, in the 1950s while working at Electrical Communication Laboratory of NTT (Nippon Telephone and Telegram Coop.) in Japan. It steadily developed to form the basis of modern quality engineering. It has been well accepted by Japanese industry, and was introduced to US in the 1980s, then to Europe. Today there are many successful industrial implementations of the method, while actively taught at educational institutions as well. The method is still under development with industrial practices.

From the standpoint of product and process design, Taguchi Method is essentially an approach to robust design, and is called Off-Line Quality Engineering in this specific sense. The core part of the method is parametric design, where control factors and their values are determined in order to minimize the sensitivity of product quality variations with respect to noise factors during product usage. The basic idea is not to try to eliminate noise factors, but to make product design most insensitive to noise factors. Before performing parametric design, a system design phase is assumed, where a product structure is fixed. In this sense, Taguchi Method is used in combination with other design approaches and methods, such as QFD.

For evaluation of product quality, Taguchi Method introduces a concept of loss function. A loss function measures user's loss of using a product, which consists of loss due to product function

[5] Taguchi Method is a trademark of the American Supplier Institute, Inc., Dearborn, Michigan, USA.

variations and other interfering losses, such as cost and side effects. These losses are calculated by the mean square deviation from the target value. Product function variations come from various noise factors, such as:

- Inner noise: component variations and deterioration, etc.
- Outer noise: usage conditions and environmental conditions, etc.
- Production noise.

The issue is how to select appropriate control factors and to determine their values, which are most insensitive to noise factors.

A robust design by Taguchi Method consists of two steps:

1. Parametric Design: All appropriate control factors are first enumerated, and a necessary set of functional experiments is determined according to the method similar to the design of experiment based on predefined Orthogonal Arrays. Functional experiments can be performed by computer simulation. In such case, appropriate noise factors are added to the simulation model. The results of the experiments are evaluated by the S/N (Signal-to-Noise) ratio, which represents stability of product function characteristics with respect to noises. By observing the values of S/N ratio for each control factor, relative importance of control factors and their optimal levels can be determined.
2. Tolerance Design: For fine-tuning of parametric design to achieve a good balance of product functionality and other factors, such as cost, precise adjustments for tolerances of control factors are required. Tolerance values are assumed, and functional experiments are performed, similar to parametric design.

Taguchi Method is now expanded to deal with software and other developments. Developments are mostly driven by industrial community.

6.19. Total Design of Pugh

Pugh was recognized for his pioneering work of Total Design [102]. The methodology of Total Design provides a design framework for a structured design process model for application of design methodology in design practice by industrial practitioners. His unique contribution is called Concept Selection Process to iteratively select the best concept from a number of candidates based on some criteria using a Concept Selection Matrix (or Pugh Matrix). The method can be used not only in conceptual design stage of overall design solutions, but also for concept selection of the total system architecture, subsystems and individual components. The core of the Pugh's methodology is the Product Design Specifications. Because of the general applicability of this approach to general product development process, his methodology has been adopted by increasing number of companies. For example, General Motors had successfully used his approach in development of Saturn project.

In comparison with other methods, Pugh's methodology is simple and easy to use by design teams, which has been proven by numerous industrial usage. Although his work was developed independently from Quality Function Deployment (QFD, see Section 6.16), Pugh's work can be integrated into QFD. While the design method is called selection process, it is unavoidable that new concepts are generated when the iterative selection process goes deeper in the process based on the house of quality. There are many new developments based on Pugh's work and subsequent work from other researchers such as Enhanced Quality Function Deployment [25] and Green (Environment) Function Deployment.

6.20. TRIZ

TRIZ, the Russian acronym for the Theory of Inventive Problem Solving, encompasses a series of tools and a methodology for generating inventive solutions for problem solving [6,7]. It was formed through the observation of invariants inherent to technical objects evolution and manual analysis of forty thousand innovative patents, of which the applied inventive solutions were mapped onto a small number of generally applicable inventive principles through inductive reasoning.

For problem solving in TRIZ, a specific problem is mapped to a more general contradiction specification, solved through the TRIZ toolset, and mapped back to the specific situation. The TRIZ methodology focuses on the notion of ideal final result and leads the user in a converged process toward inventive solutions for a specific problem in refusing compromises as a possible outcome. This approach contrasts with other creativity techniques, such as brainstorming, which are based on the interaction between ideas for triggering new proposals, and generally preferring a large quantity of ideas. Moreover, the identification of contradictions and the application of the solving principles highlight possible lacks of knowledge and consequently imply a systematic direction to integrate new competences and technologies. Apart from problem solving, TRIZ also encompasses generalized development laws to predict technical systems evolution [23], differentiated from most other approaches as it is not based on specific historical observations.

6.20.1. Industrial applications

Some companies only integrate specific TRIZ tools, or implement simplified innovation methodologies based on TRIZ [154], while others, such as Samsung, go to great lengths educating employees in "pure" TRIZ. This, and the fact that success or failure is often not publicized, make it difficult to measure the industrial success of TRIZ. Some indication of its success can be derived from inquiries within the German industry classifying TRIZ as an effective approach to problem solving [114], and indicating a "rather high" to "very high" economic benefit obtained from using TRIZ for 57% of the companies [50]. These findings are supported by a growing company attendance of TRIZ conferences and an expanding subscribers base to a leading TRIZ journal [38] indicating a high interest from industry.

For example In 2000, the Samsung Advanced Institute of Technology hired TRIZ expert Shpakovsky and recognized his work two years later with a corporate award stating that his contribution saved Samsung approximately $91 million, and led to an improved R&D performance [140]. At the 4th Japan Invention Machine User Group Meeting in 2003, Samsung presented a case where TRIZ was applied on a DVD Pickup component leading to cost savings of $77 million, and a 33% increase in reliability [73].

6.20.2. Educational experiences

Since TRIZ roots are situated in the former USSR and its development was largely conducted outside typical academic environments, most first generation TRIZ experts speak Russian only. This has hindered the fast, international spread of the methodology. However, some involved educational/research centers exist outside Russia, including the European TRIZ association which compiled a list of academic institutes [38]. Having a steep learning curve, TRIZ requires months of training, and since most educational institutions teach TRIZ as a course or part of a more encompassing course, students can only be exposed to the basics of TRIZ. However, some dedicated master programs exist, e.g., INSA's AMID (Institut National des Sciences Appliquées de Strasbourg, Advanced Master in Innovative Design), and many TRIZ experts also offer TRIZ courses geared towards industry. Recently, the European Commission also decided to support a project aimed at attracting secondary school students to the study of TRIZ [128].

6.21. UDT

Universal Design Theory (UDT) was developed by Hans Grabowski and his group in Karlsruhe in late 1990s [45,46]. It combines findings about product design from various scientific disciplines in a consistent, coherent and compact form. It takes common features of the different scientific domains into account in order to generate generally accepted statements with regard to the explanation of things and the way of looking at them. While a general design theory focuses on generic, discipline-independent knowledge, Universal Design Theory in contrast encompasses both generic, discipline-independent knowledge and discipline-specific knowledge about design. UDT integrates a broad variety of engineering domains, such as mechanical engineering, material science, information science, chemistry, chemical engineering or pharmaceutics. This also includes the interfaces between the different design decisions. Accordingly, it serves mainly as scientific basis for rationalizing interdisciplinary product development with respect to efficiency and reliability. To create and establish a Universal Design Theory, two problems need to be focused: the problem of universality and the problem of applicability in industrial practices.

6.21.1. Universality

The process of designing products requires many different skills and competencies, which applies to, for example, mechatronics product development. Design teams comprise of designers and engineers with a wide variety of knowledge and educational backgrounds. To meet this high demand for interdisciplinary product development and to enhance cooperative interdisciplinary teamwork, an overall framework for a Universal Design Theory must be created because engineers with different backgrounds are still incapable of understanding each other. In this respect, the development of a common design process model would be an important milestone.

6.21.2. Practical applicability

In general, the formal description of requirements is the first main step in any design process and provides the basis for a successful product development process. Accordingly, the complete and correct specification of a task will be represented by a certain set of requirements that are finally met by a design solution. Product design maps these requirements onto a set of possible design parameters. If the requirements are completely defined and correctly specified, a target-oriented product development process is possible. Therefore, to make a UDT practically applicable the mapping process has to be described by so-called constructive statements in an explicit and complete manner.

6.22. Ullman

Ullman's approach to design focuses on mainly mechanical design process and associated techniques and experiences [148]. His methodology is also considered as a systematic design which includes product definition, development of design specifications, conceptual design, detailed design and development, and product testing. Conceptually, this is an approach not much different from those reported in literature.

However, the significance of Ullman's design method is in its practical applications. Ullman uses design example such as bicycles to describe step by step of design process, from the conceptual design to final product finishing. This attributes to his significant real world design and engineering experiences in design education and practical design and development of real world products. He has applied his method in various applications in developing new products, and through consulting and training of engineers in various companies including Boeing and Hewlett Packard. This kind of experiences and feedback from practical applications allow him to refine his work. For example, the latest edition of his book has included various materials from practical applications such as customer needs in specific sense, creativity, synthesis of ideas, visualization, and success factors.

One important characteristic that separates Ullman's method from others is the attention to the details occurred in real life design process. This can only be done through focused efforts personally. For example, concurrent design is usually described in a teamwork in developing products. The process models, knowledge and databases and product information modeling would be generally described as technical contents. In Ullman's approach, the key concept is communication which must be built upon shared understanding of terminology used in design. Team members must use the same terms to describe objects, processes, methods and actions. Costs, quality and time to market are recognized important factors for success of product development, and his design method measures success by incorporating these factors in design processes. This level of details makes Ullman's method easy to use in industry as well as in education.

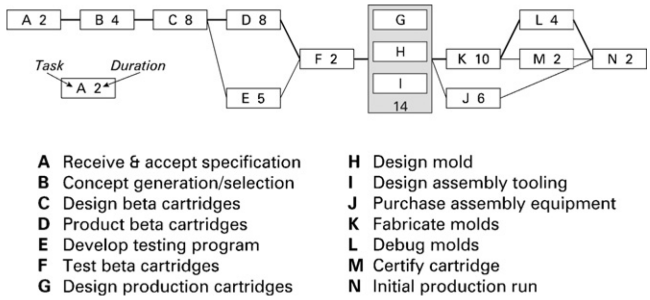

Fig. 17. Concurrent product development process of Ulrich and Eppinger [147].

6.23. Ulrich and Eppinger

The method of Ulrich and Eppinger [147] is also often used for design education. The book focuses on (complex) "product development" than just engineering design. The book therefore begins with intensive descriptions about product planning, product definition, as well as marketing consideration. For engineering design, they emphasize systems architecture viewpoints including, for example, modular architecture. In addition, they stress manufacturing considerations (DfX, cost, etc.) and process aspects (process concurrency) (see Fig. 17).

According to Ulrich and Eppinger, product architecture works as a specification wherein functional elements are ordered in "physical chunks". Physical chunks are elements every component contains to fulfill a product function. Decisions on the product architecture considerably affect the total process of product development. An important characteristic of architecture is whether it is modular or integral. Modular architectures are composed of chunks with a specific set of functional elements that have well defined interactions with other chunks. Integral architectures, on the other hand, do not have such interactions.

Actions are:

- Make a schematic representation of the product.
- Cluster components within this scheme.
- Make a hard geometric layout.
- Identify fundamental and incidental interactions.

7. Evaluation and discussions

As obviously shown in Section 6, some of DTM are well known, often cited, and commonly used in research, education and industry. However, many other theories and methodologies are used locally at the institute that developed them for teaching or limited industrial applications. Among other things, design theories are not commonly taught.

Within the category of design methodology in Table 1, Pahl and Beitz [98], Ullman [148], and Axiomatic Design of Suh [123,124] are most widely taught at educational institutes. In addition, the textbook of Ulrich and Eppinger [147] is also widely used particularly in North America but as a textbook for "product development" rather than for "engineering design". Except for

Table 3
DTM widely taught and widely used.

	General	Individual
Abstract	• Design theory (GDT, UDT) Widely taught	• Math based methods (optimization, Axiomatic Design, Taguchi Method • Computer programs
Concrete	• Design methodology (Adaptable Design, Characteristics -Properties Model of Weber, Contact and Channel Model of Albers, Emergent Synthesis, Hansen, Hubka & Eder, Integrated Product Development of Andreasen, Koller, Muller, Pahl & Beitz, Roth, Ullman, Ulrich & Eppinger) • Methodology to achieve concrete goals (Axiomatic Design, Design for X, Design Decision Making Methods, DSM, FMEA, Pugh's Total Design, TRIZ, QFD) • Process methodologies (Concurrent Engineering, DSM)	• Design methods Widely taught and used

Axiomatic Design, industrial applications (success stories) are not so common.

In contrast, most of "methodologies to achieve concrete goals", such as DfX and Total Design of Pugh, and "process technologies" such as concurrent engineering are also widely taught and exercised in industry. This also applies to the category "math-based methods" such as Taguchi Method. Table 3 contrasts methods "widely taught" with those "widely taught and used. In summary:

- Design methodologies are widely taught but find less industrial applications.
- Methodologies to achieve concrete goals as well as process technologies are widely taught and used.
- Math-based methods are also widely taught and used.

What are, then, the differences between those "widely taught" and "widely taught and used"? Obviously, the former, i.e., design methodologies focus more or less on functional design and embodiment design, rather than how to achieve concrete performance goals such as cost, quality, and time. Naturally these goals or performances are more important for routine design which occupies the majority of design cases in industry than completely new design. For routine design, innovation in functional design and embodiment design is less necessary, so design methodologies are not appreciated.

However, increasingly industry started to realize the importance of innovative design and for this reason, e.g., TRIZ as a method to enhance innovation capabilities is popular among industry. In other words, those classic design methodologies emphasized systematic design beginning with functional considerations, which was understandable from historical background, but at the same time failed to stress how to achieve innovative design. Therefore a challenge is to demonstrate innovative design cases made possible with those design methodologies, just like TRIZ did.

Among those representative textbooks of DTM, Table 4 compares Axiomatic Design of Suh, Total Design of Pugh, Ullman and Systematic Design of Pahl and Beitz. While it is absolutely impossible to state which one is the best, the choice depends on the application and designer's skill and experiences.

Then, interesting questions to academic researchers arise: Do we still have to teach design methodology even though they are not seriously used in industry? How about design theories? Do we need to teach them at all?

The answers are not easy and can be multifold. First, particularly in teaching design methodologies, teachers should emphasize how to arrive at innovative new design with the methodology rather than well-known routine design cases. The effort of Albers's group at Karlsruhe in Section 6.5 is a good example in this direction. Second, it is important to realize that DTM should be taught for future usage possibilities. Most of DTM deal with fundamental subjects that need to be taught anyway to help students to understand complicated design processes easier and to organize their knowledge about product development, even though they may not find immediate use. Without fundamental knowledge about DTM, one might not be able to understand function, which is a concept virtually in any product development processes. The authors' answers to these questions are, therefore, positive that we should teach at least one or two of variations of DTM ideally from both design methodologies and design theories. To be able to teach DTM more effectively, in addition to understanding of the theoretical aspects of DTM, teachers should be competent in using these methodologies to design products and/or systems. The practical experiences are critically important in effective teaching of DTM, which are only possible when close collaboration between academia and industry is available.

In surveying various DTM, it is almost shocking to find out that many of them do not reflect modern product development activities. We identify three important aspects:

- Complex multi-disciplinary product development (such as mechatronics).
- Further advances in digital engineering and virtual engineering for better collaboration.
- Globalization in product development.

The first aspect results from increasing variety of products and the integration of different domains (e.g., mechatronics) to meet increasingly diversified requirements [136]. Besides traditional requirements such as function, costs, quality, and time, recently it is also mandatory to meet such requirements as sustainability, life cycle aspects, and product-service systems aspects. Complexity in product development has been addressed by the CIRP community and complexity management is key to better product development (e.g., [35–37,61,111,112,125,126, 135,164]). However, tools that can solve various types of complexity are yet to be developed. Additionally, the lack of customization potential of DTM to be adapted to industrial requirements is one of the obstacles [82].

Increasing multi-disciplinarity and associated complexity of products requires collaboration between stakeholders of different domains [135]. This trend requests sophisticated management of product development processes that most of the currently applied methodologies neglect. While concurrent engineering has made a significant success in integrating, for example, manufacturing and design, this is far from sufficient, which is clear for mechatronics product development that involves mechanical design, electronics

Table 4
Comparison of design methodologies.

Design methods	Axiomatic design (Suh) [123–125]	Total design (Pugh) [102]	Mechanical design process (Ullman) [148]	Systematic design (Pahl and Beitz) [98]
Advantages	*Education*: Theory-based, systematic and fit advanced academic settings such as graduate courses	*Education*: Simple and easy to learn and follow. Does not require significant pre-requisite training	*Education*: Has been used successfully for mechanical engineering design and training courses	*Education*: Has been taught successfully in many mechanical engineering design and training courses
	Practice:	*Practice*:	Has been continuously evolved and revised to capture new development of engineering design fields	Has been continuously updated and revised to capture new development of engineering design fields
	Generally applicable for all kinds of design activities ranging from organization design to complex system design	Relatively easy to follow by practitioners	*Practices*:	The book is now complete in covering all major topics in mechanical design
	Has a large number and wide range of examples for users to follow	Has been used in a wide range of product design and consulting activities by practitioners with proven record of usefulness	Has been used for some simple product designs	*Practices*:
	Can be an effective tool in analysis in addition to design activities			Has been used for some product designs
Disadvantages	Not many design instructors have used axiomatic design for practical design work nor attended training for teaching it. Required significant training to use the theory and method in product design. More suitable for graduate engineers	Since introduction, the field of engineering design has been developing. However, this method has not been continuously improved and less used now than in 1990s	Has not been widely used in industry and limited to use in mechanical product design	Being based on the authors' long experiences, while the theory and book look appropriate even for undergraduate education, they are much deeper Can easily be misused. Students often use morphological charts to justify their own intuitive ideas Should be used for graduate engineers and academics

design, and control software design. Often, the insufficient integration tends to end up with an architecture level problem such as "solving a mechanical design failure with control software".

Furthermore, development methodologies mostly focus on phases and the outcome (products, services, software, systems), but not on the engineers and organizations applying them. Accordingly, appropriate methods need to be developed within DTM fields that consider the collaboration of a heterogeneous network of product developers, representing different domains, life cycle phases, and companies characterized by different cultures and individual backgrounds [85].

This aspect has been increasing its importance due to the recent rapid globalization trends, which is the third trend, starting from out-sourcing, off-shoring, to electronic seamless integration of geographically distributed product development centers.

Therefore, research in this area should result in advanced digital engineering and virtual engineering that allow for better collaboration [15,16,132]. Most of traditional DTM do not take into account potentials offered by ICT technologies since at the time of development of those methodologies computers were about to be developed [82]. Nowadays, ICT technologies and specific application systems are a prerequisite to avoid physical prototypes, which is necessary to obtain some of the main product development objectives. As a consequence, academic researchers should use more intensively the opportunity to develop appropriate development methodologies with the direct integration of computer technologies.

In summary, compared with methods widely taught in academia and used in industry, design methodologies find less industrial applications for the following reasons:

- They emphasize too much on functional design and embodiment design only, meaning less useful for routine design.
- They addressed systematic design very well but not innovative design.
- Teaching DTM often lack practical applications that lead to future usage possibilities besides theoretical aspects.
- Current DTM insufficiently address various issues in product development activities including complex multi-disciplinary product development, advances in digital engineering and virtual engineering, and globalization in product development.
- Current DTM insufficiently address behavioral and organizational aspects of product development processes.
- Current DTM do not consider full potentials of ICT technologies.

This list of shortcomings of current DTM can be considered research issues and targets to close the gap between academia and industry. However, this requires persistent effort of the both sides. Academia needs to focus more on industrial applications and various practical aspects (such as innovation, multi-disciplinarity and better use of ICT), while industry has to be open to recent development of DTM without preconceptions. Not just research, DTM can also be emphasized in the context of recurrent education of engineers in industry.

8. Conclusions

This keynote paper is an attempt to obtain vigorous evaluation by collectively gathering neutral information about DTM, particularly focusing on applications of design methodologies in design education and design practice.

First a number of categorization methods for DTM were introduced. Such a categorization is useful to obtain an overview of the current development of the DTM field.

Based on collective efforts of authors and other contributors, a number of theories and methodologies were reviewed. Some conclusions are drawn from this review.

- Design theories are not widely taught.
- Design methodologies are widely taught but find less industrial applications. One reason is that they do not emphasize innovative design. The other is that they are not useful for routine design or improvement design, which is the majority in industry.
- Methodologies to achieve concrete goals as well as process technologies are widely taught and used.

- Math-based methods are also widely taught and used.

Design theories and methodologies have a value in education in helping students to easily understand fundamental concepts and to organize knowledge related to product development activities. Therefore, the authors recommend to teach at least one variation of DTM emphasizing how to achieve innovative design, although the choice of a particular theory depends on the context and possible applications.

The paper also identified the insufficiencies of the current DTM. The following is a list of potential future research topics.

- Considerations about product complexity and multi-disciplinarity.
- Consideration of increasingly complex requirements.
- Consideration of multiple stakeholders with different cultural and educational background.
- Management of complex product development processes.
- Further integration of domains.
- Integration of advanced ICT technologies for computer oriented design methodologies and better collaboration.
- Consideration about globalization trends that requires advanced virtual engineering and collaboration methods.

The first step toward such advanced research is a survey of experts (including CIRP STC Dn members and other relevant organization) to make an inventory of their current and future research topics ([26] is a version compiled in 1995). Besides traditional survey methods, such as inquires, just like this paper, a Wiki-based survey method could be employed to improve the efficiency of the survey.

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