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Tools and techniques for product design

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ABSTRACT

For product designers, tools and techniques are essential in driving the design cycle. Nevertheless, their employment usually is implicit, while passing over e.g. the design and project environments empowering their adequate use. This publication presents an overview of approaches in structuring and using tools/techniques, based on the effectuation of creativity and decision-making in the design environment. In elaborating on characteristics of tools/techniques and ensuing ways of selecting them, the designer's portfolio of tools/techniques is characterised. Representative problems of tool/technique usage are depicted and contextualised by illustrating their industrial application. Prospects for future developments are also reviewed.

1. Introduction

In the hands of competent craftsmen, the right tools become powerful resources, which intrinsically seems to reinforce their capabilities and capacities. It more or less becomes an inherent component of their efforts to reach a specific goal. For product designers, a wide variety of working methods, best practices and software packages can fulfil that same role. Given the fact that product designers habitually balance on the verge of arts, crafts and science, while customarily co-operating in teams consisting of designers and representatives from other fields of expertise, they might be rather discerning in identifying the set of implements to draw from. Such instruments, or more specifically tools and techniques, can significantly further design projects and the way in which those projects are executed. In most cases, tools/techniques are deployed best if designers experience them as inherent to their work; i.e. if the tool/technique in itself does not compel attention in its application. The tools/techniques work best if they are 'ready-to-hand' [109] and do not intrude with the craftsmanship of the designer. At the same time, the design environment changes rapidly, as, for example, new tools/techniques emerge, information alters its role [222], virtual or augmented reality comes within reach (e.g. [21]), and also the characteristics of products that enter the market are subject to change (e.g. [141]). In such circumstances, tools/techniques can no longer only be seen as inherent and implicit. They alter into 'present-at-hand' [109]: their implementation and employment calls for attention and interplay of the designer as well as of the company.

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Because designers and companies encounter tools/techniques that explicitly manifest themselves, it is purposeful to survey the conditions in which such tools/techniques find employment. Research on this topic is limited [157], although tools/techniques for product design are key with respect to design efficiency [17]. Even more, a lack of employable tools/techniques is, traditionally, already seen as an internal obstacle to the successful introduction of new products [24].

The rationale of this publication is certainly not based on compiling exhaustive lists of tools/techniques, as that would not do justice to the complexities of the design environment, nor would it benefit designers in their work. At the same time, no enumeration can possibly be complete. Moreover, the half-life of any observation on a specific tool is surprisingly short. Consequently, in this publication the focus is on the embedding of tools/techniques in the context of the environment in which they are used.

The structure of this publication is based on the driving impetuses of the design process and on the different functional objectives of product design. Creativity and decision-making are introduced as major components of design projects. They have a major impact on design efficiency, bearing a strong relation to the employment of tools/techniques in the design environment. Given the wide use of the notions tool and technique, definitions are derived that do justice to the design environment, but will not act as straitjackets or fault-finding in describing the role of tools/techniques. With these definitions, the designer's work is dissected to allow for depicting the relation between design activities, product/project typification and the characterisation of tools/techniques. In this, the ever-changing and reactive design environment emphasises the relevance of the many life cycle aspects that play vital roles. As this environment entails much uncertainty and ambiguity, their influence on tool/technique employment is illustrated. To contextualise characterisations of tools/techniques, exemplary industrial embedding is described. Based on the overviews given in this publication, future developments will be proposed and commented upon from the application, research and development viewpoints for tools/techniques.

1.1. Scope

Although much of the reasoning in this publication is applicable to a wide variety of product types, the background of the work presented here stems from an environment that aims at engendering discrete, physical products. For example, the reasoning might well be applicable to the (integrated) design of services [166,185,211] or even the processing industry; however, the wording and terminology is geared to and based on design cycles for discrete products. In this, focus is explicitly on the design of these discrete products, rather than on the ensuing engineering tasks covered by product development.

Nevertheless, even for these discrete products, the staggering amount of existing products immediately illustrates that it would be an endless task to group products according to 'classical' product classification methods (e.g. [132,192]). Even more elaborate classification methods (e.g. [251]) are only appropriate for a specific domain of the entire range of products. Consequently, another way to classify products is required. Rather than function, geometry, material, required processes, etc. this typification is based on more abstract properties of products. However, in this case, a relevant set of appropriate properties has to be selected, in order to avoid the hazard of arriving at an infinitely large set. In literature, ample attention has been paid to this problem, with varying results. An important contribution [117] values the mutually independence constraint of the properties of so-called technical systems. A categorisation of properties and a 'model of models' (based on [198]) is used to arrive at the co-ordinate system in the model shown in Fig. 1.

Novelty manifests itself in unconventional ideas, features and conceptual combinations that 'are not obvious from the state of the art', whereas maturity relates to the firmness of a system design. Complexity is interpreted in direct relation to risk of failure. Evolution of systems, in terms of the model, tends towards lower novelty, higher complexity and higher maturity.

Fig. 1b shows an alternative [225] where the evolution of product development is related to the competitive insistence on higher quality, increasing complexity and lower lead times. As the determination of the quality of products in general is rather subjective, this property might be a fragile basis to compare and classify different (types of) products. Moreover, the lead-time probably is more an indication of the production process and its organisation than of a product.

These two deficiencies have been overcome by selecting a different perspective. Reasoning not from the manufacturer, but from the customer, the product can be valued against its direct requirements. This allows for the same approach of independent properties, however, the selection of properties is partially different (see Fig. 1c). The first property is complexity, basically indicating the same property as in Figs. 1a and b, but with emphasis on the complexity pending the entire product life cycle (i.e. during manufacturing, maintenance, repair, recycling, etc.). Based on the different ways in which customer-supplier relationships

Fig. 1. Different ways to characterise products.

[59] and the customer-order decoupling point (see e.g. [139,190,209]) can be modelled, the adaptability of products can directly be used. The third property is the quantity of products.

2. Problem solving, creativity and decision-making

The design of products is, and will always be, an act of craftsmanship. It is characterised by the ability to repeatedly employ problem solving, creativity and decision-making in a controlled and efficient manner to reach an adequate product definition. In this, the balance between creativity and systematic approaches strongly depends on the type of product (see Fig. 1), where the difference between routine and non-routine design as well as between incremental and breakthrough innovations plays an important role [83,87].

2.1. Creativity

Irrespective of the context, the team involved and the tools, techniques, methods and frameworks that support the design team, it will always be the ingenuity and inventivity of the designers that provide for and ignite the creative sparks that decisively discern individual product development cycles. With this, designers are really at the heart of product development. This is all the more true, because the product design cycle consists of a set of activities that has no equivocal starting point; it has a result that is not known on beforehand and that is reached by a trajectory that is capricious. Therefore, a design cycle thrives on creativity as the main propulsion mechanism, producing the vital incentive for the evolution of the product definition that goes with the headway of the product development project. Consequently, creativity is the cause of progress in development cycles, but may simultaneously hamper the predictability thereof.

Infused by the unique role it has in development cycles, literature addresses the phenomenon 'creativity' from a variety of viewpoints, ranging from cognitive aspects [33,140], via experience [7,116], team work [250] to educational aspects [61,144] and investments [229]. Resulting from a detailed study of definitions of creativity [35] is the definition: "creativity occurs through a process by which an agent uses its ability to generate ideas, solutions or products that are novel and valuable".

What seems to be a common factor in most literature on creativity is a focus on its realisation: preconditions, means, environment and challenge. Also, the differences between 'personal' and 'social' views on creativity – depending on who perceives the newness and usefulness – are recognised [163]. A discernment that is contributive from the perspective of the overall design cycle is the dichotomy between the 'content' of creativity and its 'structure'. It is evident that a designer will always observe the coherence between the mechanisms of creativity and the subjects these mechanisms are applied to. Junior designers might explicitly struggle with this split, whereas experienced designers might have grown to implicitly value the amalgamation of the two.

For design teams, it is impossible to adequately tackle a design cycle and have a meaningful overview over the design tasks if the content and structure of the work are too intertwined.

Creativity is a means to an end: it explores beyond the frontiers of the current product definition. The results of such explorations are contributive, much more than the initiatives that caused those results to be achieved. Consequently, creativity is not the only precondition for progress in development cycles: the possibilities opened up by creativity must be assessed, elaborated and incorporated in the overall design cycle to make actual headway. Moreover, it is the progress in the design cycle that determines if there is room and demand for a next creative step [248].

The progress in design cycles is characterised by the myriad decisions taken by members of the design team (and selected other stakeholders) that subsequently, concurrently, conjointly but also contradictorily raise the extent and level of the product definition (see Fig. 2 [182]). All these decisions, in a sense, are the building

Fig. 2. Decision process in the context of business and environment.
Redrawn from [182].

blocks that construct the design cycle [106,107,111,143]. Obviously, creativity is merely one of the occasions for design decisions to be made; decisions can (or need) also be made following a wide variety of other causes, ranging from changed circumstances or aims, via new insights or simulation results, to sheer routine project advance. Even in such cases, often quite some creativity is involved in preparing an adequate decision context, i.e. a situation that allows for reaching a well-underpinned decision. This becomes all the more relevant in observing that most decisions cannot be taken based on complete, correct, flawless, unequivocal, transparent and objective information, criteria and aims. Consequently, at the prevailing status of the product definition, it is extremely difficult to adequately determine effective and efficient next steps to consolidate the right prospects with their varying consequences and scopes. Especially pre-sorting the tactical and strategic directions for design steps against the prevailing status of the product definition in the available design environment renders the design cycle a complex and challenging set of activities [73].

2.2. Decision making

Decision-making, not only in general, but also for product design has been the topic of many studies ([5,28,102,227,243]). Given the complexities sketched in the above, it is understood that the many different points of view that exist prevent the emergence of one unequivocal model for decision-making. As a common denominator, formally, decision-making can be regarded as the act or process of consideration and deciding, resulting in a conclusion or resolution especially as to future action [51].

In design, the activity of decision-making arises from the need to select the best possible course of action (or a set of optimised actions) from a set of alternatives [124]. Exploration and development of alternatives is typically an integral part of the decision-making process. Often this is not a separate step but is intertwined in an iterative decision analysis cycle [63]. Moreover, either explicitly or implicitly, such cycles adhere to the same principle of PDSA (plan–do–study–act/adjust) [60] that are employed for process improvement. This puts design decision-making in the bigger scheme of management theories. From this viewpoint, it is clear that actions/adjustments are only purposeful if they lead to consolidations in the design. Additionally, the link between design decisions and management allows for dedicated approaches for quality management (e.g. six sigma [234], TQM [162], 8D [203]).

The linearity of most decision analysis cycles (see e.g. Fig. 3 [115]) is appealing; however, due to the fact that in design generally no single decision can be seen independent of other decisions, they present a straightforwardness that cannot be substantiated. These mutual dependencies add to the already existing impreciseness and fuzziness in information, criteria and aims. Research fields like multiple criteria decision-making (MCDM [242]) specifically focuses on the improvement of decision-making in the presence of multiple, generally conflicting criteria that can be weighted and used to rank the decision

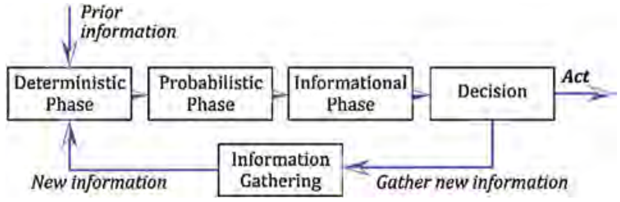

Fig. 3. Decisions analysis cycle.
Redrawn from [115].

alternatives that are available. Here, a distinction is made between multiple objective decision-making (MODM), and multiple attribute decision-making (MADM) [205]. MODM is concerned with choosing from a large, infinite, or uncountable number of objectives. MADM is concerned with ranking a finite set of alternatives. However, as both approaches are mainly concerned with the criteria in a decision, they cannot simultaneously deal with how the aims and information that underlie intertwined decisions in an adequate manner. In an attempt to resolve this, fuzzy MADM methods are developed [205]. Whereas it aims to reason with vague, ambiguous and imprecise input or knowledge [131], outcomes are convoluted to such an extent that for product designers such approaches may be considered as less useful.

One reason for the fact that information in decision-making is not effectively available is that the outcome of decisions – especially in the earlier phases of the design cycle – is registered inadequately. Consequently, subsequent or dependent decisions extrapolate on a decreasing reliability of information, leading to even more unreliable decisions. In focusing on capturing the reasons behind, and the justification of, design decisions, design rationale systems aim to improve this. Design rationale is "the documentation of the reasons for the design of an artefact, the stages or steps of the design process, the history of the design and its context" [177,264]. Generally it is attempted to make design reasoning more correct, consistent and thorough by prescribing the 'method of reasoning' that is considered to be appropriate.

3. The design environment and design methods

Next to all influences that might illustrate the multiplicity of challenges encountered by designers, there is one characteristic of design cycles that is preponderant in causing these challenges: the fact that in well-nigh all design decisions the designer is dared to simultaneously reach more than one aim. Within the characterisation of product complexity, next to the terms complicacy, opacity and interdependency [99], the striving for multiple goals has an essential impact. This so-called polytelie [68,184] (literally 'many goals') indeed addresses the fact that in every design decision usually multiple, and often conflicting, goals exist. Frequently, the vast majority of these goals is not even clear or made explicit. Moreover, as it – on beforehand – is usually not even known which stakeholders will be involved, only the subset of identifiable and expected stakeholders (addressing e.g. competitors, users and legislators) can be assessed. The outcome of this assessment is then assumed to represent all identified goals as the context of any design decision.

This polytelie is an important explanation for the non-linearity of design cycles. Indeed, it already implies that the initial design brief is probably open to more than one interpretation. What is more, many design projects do not depart from a requirement specification that is correct and complete. At the same time, requirement specifications serve as a reference for judging the available alternatives and, as such, determine to a large extent the course of design cycles [152,153,254]. Requirement specifications exist in multiple forms, at different levels of detail and with changing degrees of certainty and ambiguity. In its most essential state, the requirement specification has a so-called stated purpose as its basis: a predefined, formalised and static reference of the development process [173]. It reflects the pre-imposed requirements of (external) stakeholders, like law, marketing and safety. In addition, three types of requirements are distinguished: technical specifications, functional specifications and scenario-based specifications [151,173]. The merger of these different requirement specifications is in itself a dynamic frame of reference that evolves as the product is being defined. This provides a benchmark for assessing the current development cycle and prefacing subsequent development processes.

With the design environment evolving during design projects, the result of a design cycle cannot be assessed unequivocally. That being true, the implication is that any systematic plan for product design is bound to devaluate in appositeness. Any prescriptive design approach inherently has subjective aspects – at least in an implicit manner. Moreover, it is clear that also the reproducibility of design decisions and design cycles will suffer from this.

As a consequence, designers cannot comprehensively revert to a set of basic recipes for product design – in an environment that is unpredictable (presumably erratic) and instigating to subjectivity and directionlessness while being multi-interpretable. This contributes to the explanation of why so many design method(ologie)s exist. Many of these methods show considerable resemblance, whereas particularities seem to determine the unique character of individual methods. This makes the coherence between design methods difficult to interpret [237]. In many cases, the distinctions between the methods are explicable because of the different viewpoints that laid the foundation for the development of these methods. Such different viewpoints are shaped by sets of characteristics. There are many clusterings found in literature. An example focusing on engineering design is [253]: Macroeconomic, Microeconomic, Corporate, Project, Personal. Focusing more on an Industrial Design Engineering application is the set of product properties or factors [236]: Design, Production, Sales, Use, Destruction.

In striving for completeness, many overviews tend to become rather specific [71,119,156]. On the one hand, this may make the list of properties more useful, but on the other hand, it accordingly narrows its applicability. A compromise distinguishes four different influence types [184] (see Fig. 4): Product, Organisation, Project, People.

Given the diversities of the many existing design methods, also many attempts to categorise them exist [79,237]. After all, different approaches are possible, ranging from developing individual design methods for specific conditions and situations to tailoring design methods to the circumstances of a project. In the latter case, it might be questionable if the resulting depiction of the project still is a formal design method. However, in practice, many design methods are indeed 'tweaked' for better employability; usually this is done implicitly, driven by the experience of the designers involved. A slightly more extreme example of adapting the design method to the circumstances is the roadmap concept (e.g. [66]), in which the processes in the design cycle are not prescribed sequentially; it rather offers a framework of identifiable steps providing templates and guides for adequately addressing the design cycle. With increasing flexibility, the need for understanding how knowledge underpins the ability to adapt development cycles increases as well [76,216]. This also addresses decision-making in positioning methods and accompanying tools/techniques, from 'identification' and 'extraction' to 'diffusion' and 'maintenance' [31]. To purposefully consider such decisions, it is important to note that the capability to adequately structure the company's processes relates to the maturity of innovation processes in the company [75,77].

From a different viewpoint, research focusing on descriptive design starts from studying what processes, strategies, and problem solving methods designers use [79], aiming to understand the design process from its elementary constituents. Such approaches might adequately answer the question of how humans create designs, yet they may not be ideal in initiating and governing next steps in individual design cycles. In relation to this, one of the axioms [210] that plays a role in several descriptive design approaches is relevant: "Every design solution (that is, every artefact produced as a result of design) will inevitably change equilibrium relationships within its environment and thus create unforeseen problems." It is striking to see that a change in equilibrium is almost seen as a preclusion of understanding rather than as a driving mechanism in the design cycle.

4. Delineation of tools and techniques

In focusing on the quintessence of tools and techniques as components of design cycles in the design environment (see Sections 1 and 3), the adequate demarcation of the notions tool and technique are obvious starting points. From there, the role of tools and techniques in the design cycle can be depicted and valued.

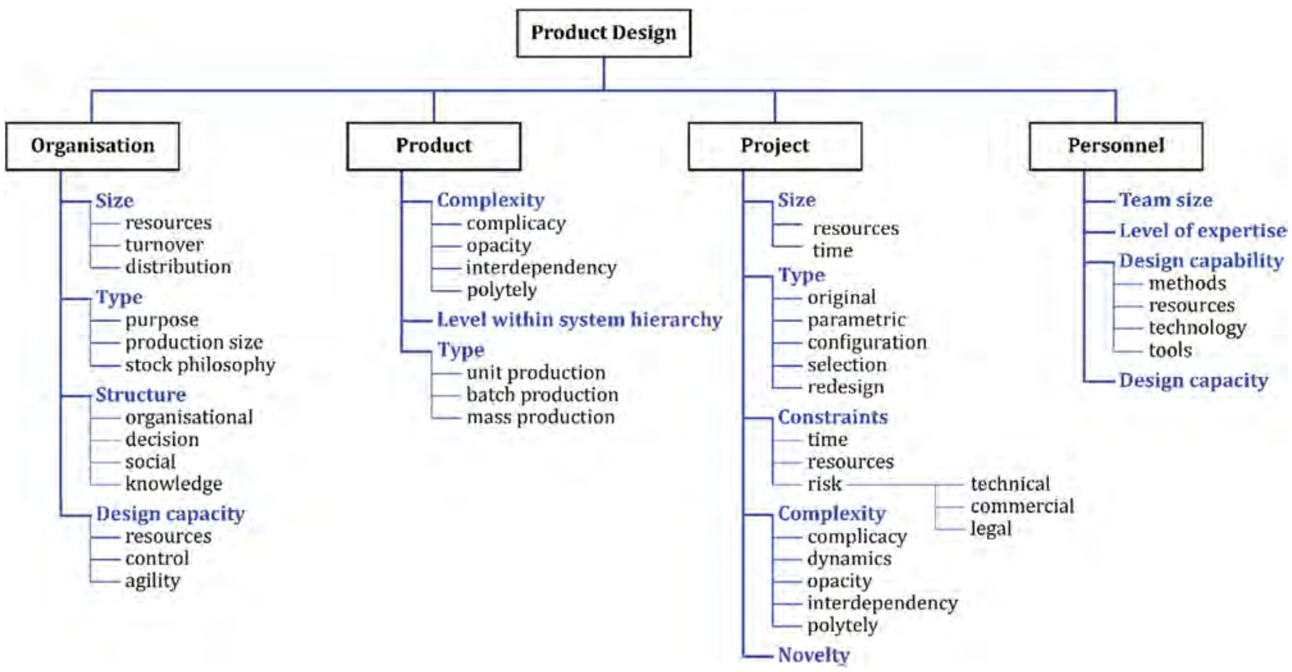

Fig. 4. Parameters influencing the design process.
Redrawn after [184].

4.1. Definitions

To start from a viewpoint that is not limited by the product design environment, a tool can be defined as:

Tool: "[...] 2.a: something (as an instrument or apparatus) used in performing an operation or necessary in the practice of a vocation or profession <a scholar's books are his tools>. [...]" [2]

Similarly, a technique is defined as:

Technique: "1: the manner in which technical details are treated (as by a writer) or basic physical movements are used (as by a dancer); also: ability to treat such details or use such movements <good piano technique>. 2.a: a body of technical methods (as in a craft or in scientific research) 2.b a method of accomplishing a desired aim." [1]

In a more explanatory way, the notion technique is also depicted as "a way of doing something by using special knowledge or skill." [4] or "A practical manner in which a certain activity is to be executed" [22].

Tools are – in the context of design – additionally defined as "... an implement that you employ to facilitate the use of a method or an aid to the use of a method." or "... manual or computer based systematic methods or frameworks that have the potential to increase efficiency in one or several phases of the product development process." [188].

In converging to their meaning in design cycles, the dictionary definitions actually do justice to the denotations that are implicitly used in literature. For many designers, tools and techniques conjointly enable them to make headway with the activities they deploy in design cycles. For that reason, methodology can be defined as "a collection of procedures, tools and techniques for designers to use when designing." [78]. Alternatively, methodology "is used for knowledge about practical steps and rules for the development and design of technical systems, based on the findings of design science and of practical experience in various applications." [16]. In this, methods represent logical sequences of phases in which tasks are completed. Fig. 5 shows that relation in a more formalised manner.

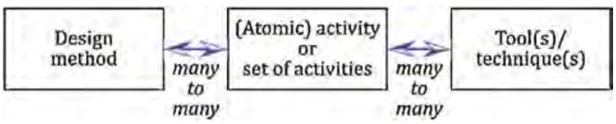

Fig. 5. Relation between design method, activity and tools/techniques.

Methodologies represent the highest level of abstraction for conceptualising problem-solving methods. Here [135,195], methodology is defined as a collection of problem-solving methods governed by a set of principles and a common philosophy for solving targeted problems [37]. At the next level of abstraction, a technique is commonly understood to be a procedure or a set of specific steps for accomplishing a desired outcome [100]. The term technique is then defined as a set of precisely described procedures for achieving a standard task. At the lowest – most concrete – level of the classification of design methods the term tool refers to instruments or certain tangible aids in performing a task [100]. In some cases, a tool is a synonym for a computer software package to support one or more techniques [195].

In the definitions, and in Fig. 5, it seems that tools, techniques and activities are independent entities, which exist in the context of the design method. However, in practice, the (use of) tools and techniques are fully embedded in and related to the environment in which the design cycle is executed. For example, many tools and techniques are useful because of the systems that are implemented in the environment. The notion 'system' relates here to, e.g. PLM, ERP, PDM, CAD and similar systems that underlie the work of the designers and are not directly under their range of influence. For example, the introduction of 2D CAD heavily influenced the verification of drawings. At the same time, the lack of expertise of designers and the limited ergonomics of CAD software in the 90s made this verification process error-prone. Sometimes, CAD is even compared to chess, being a process of 'moves' defined and constrained by the system. Later, designers who previously used drawings to communicate with manufacturing departments, created 3D models and defined manufacturing strategies with CAM tools. Yet, many manufacturers have continued to work with 2D drawings; some still do. Such an example illustrates that development or implementation of tools/techniques can be prolonged investments for designers; not only because of skills and habits, but also because of validation and robustness of tool/technique employment.

As a result, working methods for designers changed; also, IT departments developed 'control systems' (see also Section 11). In a sense, such approaches provide the platform based on which the designers can employ their expertise, often by deploying tools and techniques. Fig. 6, metaphorically, illustrates the intrinsic reading of systems, tools and techniques.

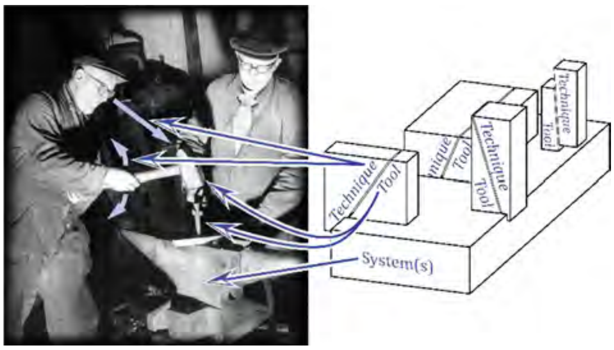

Fig. 6. Illustration of system(s), tools and techniques.

It is important to make the relation between tools and techniques explicit. After all, for a designer, these are two combined means to the same end. Sometimes they are even completely merged and conjointly referred to as e.g. Product Development Tools [58]. Having access to, or understanding of, only a tool or only a technique is rather impracticable. Both are required to execute the task at hand, even if the balance between tool and technique can vary considerably. The latter is illustrated by comparing sketching with a pencil, using a drafting tablet or by a dedicated software tool to capture product concepts. Although the balance indeed varies, the result may be the same: an adequate presentation of the designer's product concept.

This implies that rather broad definitions of the notions tool and technique are required here. A basis for this is the definition provided for Product Development Tools [58]: "... are regarded as being any artificial means that are available to [and to a certain extent used by] manufacturing organisations (and individuals within it), in order to support them in understanding, establishing, executing, and controlling tasks and activities, and solving problems, in the context of product development."

It is understood that such an encompassing and compliable definition does indeed cover all methods, tools and techniques as referred to in this publication. However, it becomes rather prescriptive in nature, thus not aiding the designer in purposefully dealing with tools and techniques. Given the range of available tools and techniques, this may seem justified; yet, the same range calls for effective ways of selecting and implementing them. Moreover, the dimensions in which tools and techniques differ are manifold: scope, background, aim, flexibility, adaptability and level of aggregation, to mention just a few. In literature, enumerations of individual tools and techniques are given to characterise the overall impact of tools and techniques (e.g. [98,112,223]). Although very relevant, they often approach the topic from one specific setting or perspective, thus not needing to be objective as concerns the dimensions like the ones mentioned above. A particular reason for this might be that, more often than not, tools and techniques 'emerge' from everyday practice or theory and, only at a certain point in time, they are made more explicit and formal. Consequently, many tools and techniques are the result of combined collective effort of for example academics and professionals [58]; that result is than added to the toolbox of the design community. Such collective efforts can be based on short-term results, but often, structural co-operation leads to more strategic solutions. An example of the latter is the fundamental need to adequately predict helicopter aerodynamics. Here, more than 40 years of joint efforts between universities, research institutes and industry led to the development of aeroelastic software suites like Camrad in the US or Host in Europe.

For the purpose of this publication, it is important to define tools and techniques in such a way that justice is done to the unique role of designers and their creativity in the design environment. Therefore, a definition of 'tools and techniques' that is instrumental in product design cycles, giving the complexities of those cycles as described in the previous sections is:

> "*In product design, the combination of tools and techniques is a means to apply and exploit the skill and craftsmanship of product designers and design teams in order to examine a solution path (or alternative) while pursuing a specified aim in the context of a chosen or enforced design method or approach.*"

4.2. Standards

It is clear that mere definitions cannot change the way in which designers use tools and techniques. As with many other constituents of the design cycle, formal standards may add relevance to the notions. Nevertheless, the notions tools and techniques are often treated as implicit givens. The most relevant depiction is found in ISO/TS 16949:2009 [123]. Stemming from an automotive background, (based on ISO 9001:2008 [122]), it simply considers tools and techniques to be part of the (human) resources that play a role in quality management of the manufacturing of customer-specified parts, for production and/or service. At the same time ([123], Section 6.2.2.1), it indeed sees tools and techniques as mechanisms that can be applied by individual designers:

> "*The organisation shall ensure that personnel with product design responsibility are competent to achieve design requirements and are skilled in appropriate tools and techniques. Applicable tools and techniques shall be identified by the organisation.*"

The standard does not specify what is exactly meant with 'applicable' tools and techniques. Earlier (and now obsolete) standards like QS-9000 [226] are more elaborate, although here, the combination of tools and techniques is referred to as skills. Designers should be qualified in the following skills:

- Geometric dimensioning and tolerancing (GD&T).
- Quality function deployment (QFD).
- Design for manufacturing (DFM)/Design for assembly (DFA).
- Value engineering (VE).
- Design of experiments (DOE).
- Failure mode and effects analysis (DFMEA/PFMEA, etc.).
- Finite element analysis (FEA).
- Solid modelling.
- Simulation techniques.
- Computer aided design (CAD)/Computer aided engineering (CAE).
- Reliability engineering plans.

Unfortunately, this enumeration is not convincing concerning contents, completeness or feasibility. Therefore, many companies have – in their own formulation of their quality management systems – added additional skills for their designers. Obviously, the completeness of any of such lists is questionable; additionally they might draw on the flexibility of design cycles. Another important observation is that the list in the standard presents skills that are incomparable as concerns level of aggregation; some of the skills address individual techniques, whereas others (e.g. solid modelling) may cover a large part of the design cycle.

From a completely different viewpoint, standards stemming from the product definition itself may influence the process. After all, many standards (e.g. STEP, IGES, JT) underlie the way in which information is transferred between tools. All too often, the limitations, perspectives and assumptions in the definition of these standards have a considerable influence on the work of designers. With this, standards turn out to be more than 'languages to exchange information'; they can become either restrictive or they can be seen as the enabling frame. In this, it is relevant to distinguish between standards that allow to construct content in a flexible manner [108,138], and those that explicitly define how and which content is covered.

4.3. Context

In practice, (industrial) designers use an expanding inventory of digital and conventional design tools during their design practice [89,199,202,218], helping them to visualise, communicate and develop design ideas [89,92]. With an expanding array of tools available, the design practitioner's understanding of the benefits of individual tools is important [64,65,164]. The ability of the designer, influenced by experience of practice, to use the right tool in the conceptualisation, development and detail of design is critical [230]. The combination of tools and techniques are the continuation of the craftsmanship of the designer. They allow the designer to interact with the design problem and to give and hold grip on the project. Obviously, tools and techniques can vary considerably in scope, impact, preconditions and level of aggregation. Moreover, tools can often be seen as consisting of other tools. Equally, a technique might consist of techniques that on their own are applicable and useful as well. This implies that it is impossible to make a hierarchical arrangement of tools and techniques that objectively, unambiguously and explicably pegs down an overview that allows designers to purposefully select, value and access those tools and techniques.

5. Characterisations of tools and techniques

In capturing the essence of tools/techniques, it does not make sense to collect endless lists of existing tools and techniques and attempt to capture their potential contributions from different perspectives. Not only would such an approach result in incomplete lists, it would also – inevitably – lead to the occurrence of unclassifiable tools and techniques, yielding definition issues that are hardly constructive. This implies that attempts that are based on the typification or classification of product types [193] can only lead to disputes on hierarchies.

Alternatively, tools and techniques are here grouped according to their characteristics as concerns their scope, breadth, performance and aim in the design cycle.

5.1. Position in the design cycle

An obvious steppingstone for clustering is available according to the stage of the design process. The identification of phases in the design cycle is inherent to most design methods; therefore, a wide variety in definitions exists. However, an enumeration that is quite common is [194]: Planning and Clarification/Conceptual Design/Embodiment Design/Detail Design.

Such a list is instrumental in clustering the activities in the design cycle. With this, also tools and techniques related to these activities can be grouped. However, because some tools support one specific action and some tools support a considerable section of the development cycle (see Fig. 6, right side), a classification scheme that is all too granular would either disregard broadly employable tools, or continuously duplicate them. Therefore, classification against the development phase usually results in a sectioning that is rather too generic. For example, a classification based on e.g. concept design, development design and detail design [14,48,201,217] becomes rather useless.

5.2. Type of effect

Because tools and techniques are inherently employed to achieve a certain result, the type of (expected) result is an obvious means of classification. If expressed from the viewpoint of the user, the phenomenon/effect of the tool and its interaction can be depicted [58,129]. The following classes of tools would be, at least, possible to be distinguished:

- Tools acting on the creativity of the practitioners.
- Tools based particularly on the knowledge of the object.
- Tools that improve the way of working, forcing practitioners to work in a more scientific way.
- Tools that encourage the use of certain technical means, etc.

5.3. Characteristics of the operators

In elaborating the role of the user, and recalling the position of the operator as the fundamental factor in any tool in the design cycle, the way in which these operators understand and apply the tools is essential. Some tools are restricted in their application because they dictate certain definite conditions of operators. Consequently, it is possible to identify, for example, the following classes of tools [58]:

- Tools directed at certain individuals only, or groups only, who hold certain specific skills or types of knowledge.
- Tools in which the application is conditional to the availability of certain working means, such as computer software, hardware, infrastructure, organisation.
- Tools that require certain definite working conditions, limiting their application restrictive to certain situations.

5.4. Scope and target

Compared to the systems that underlie the design cycle (see Section 4), tools and techniques are usually more limited in scope: they typically relate to more individual activities. However, this does not yield an obvious way to depict the tools and activities. After all, the use of tools and techniques might cover one or more activities, addressing different aspects from different viewpoints.

Moreover, activities can be considered to consist of other activities. This indicates that tools and techniques will be interrelated at different levels of aggregation and detail. It also implies that the granularity of the design cycle will vary considerably; leading to overlap, gaps, but also to recursivity.

Generally, design tools and techniques are used to support, improve or enable (the course of) design processes as proposed by design methods. Similarly to design methods, some tools or systems underlie design processes in general (e.g. CAD systems), while other tools specialise in facilitating selected parts of the process. Examples include tools that support a specific design method (e.g. 'Innovation Workbench' [265] for TRIZ), specific design activities (e.g. feature recognition software for production preparation activities [PART] [113]) or specific design subjects (e.g. the bearing calculation tools on the website of a manufacturer). Depending on factors like the scope, frequency of use and degree of integration in the process, some design tools are useful but dispensable additions to the course of the design process, while others make or break the success of the process.

With the different types of activities addressed by designers, the type of tools and techniques vary as well. Tools can vary from actual physical tools, via generic implements that are technique-independent to dedicated software packages that purposively support the related technique [204].

5.5. Aim

For designers, it is so obvious to use tools and techniques that they often do not explicitly relate that use to a formal aim or goal. Nevertheless, it is relevant to examine why tools and techniques are used. That gives rise to the question what the added value of a tool/technique combination can be. Generally, the answer to this question is simple: the added value is that designers are better capable of doing their work, in a manner that is more applicable, effective or efficient. Consequently, designers tend to express those benefits in terms of the overall design cycle. In essence, the moments where these benefits are most visible, are the points where (the consequences of) decisions manifest themselves. Therefore, it is extremely interesting to see that the models for design decisions bear close resemblance to the phasing in design methods for complete design cycles. This again draws attention to the factuality of design being a sequence of decision-making steps (see Section 2.1).

In abstract terms [184] and based on formal logic [196], during synthesis activities in the design process the designer uses abductive reasoning [48,262] (or "productive" reasoning [159]) to create a design proposal based on presuppositions or protomodels. This proposal is then analysed using deductive reasoning to determine the performance characteristics of the design. The inductive evaluation of the characteristics leads to further refinements of the design and the cycle is repeated. The process is therefore based on the use of pre-structure as an initial solution, which is refined by a conjecture-analysis evolutionary process [13].

To elaborate on this, it is stated that designers evaluate solutions by comparing the alternatives and deciding which is best [245]. In doing this, designers take four basic actions:

- *Establish need* or realise there is a problem to be solved.
- *Understand* the problem.
- *Generate* potential solutions for it.
- *Evaluate* the solutions by comparing the potential solutions and deciding on the best one.

Alternatively, the actions are also referred to as 'Evaluating, Validating, Navigating and Unifying' [101].

Additionally, if designers want to communicate the results of their deliberations to anyone else or record it for later reference, then a fifth action is also needed:

- *Document* the work.

For designers, it is inherently advantageous to employ tools and techniques that address a larger part of the design cycle; after all, calling forth skills for a limited number of tools and techniques is far less complex than doing that for many individual smaller tools and techniques. In the latter case, it is also extremely difficult to maintain an overview and to ensure that all activities are based on the accurate information status and evolvement of the product development. This is also related to the PDSA cycle mentioned in Section 2.1; from a project management point of view, limiting the number of tools and techniques that are part of the design cycle is certainly favourable. At the same time, it certainly does not do justice to the complexity and dynamics of design trajectories.

As a side effect, this aspect may also explain the tendency of tools/techniques and other (software) systems to slowly expand to incorporate more and more functionality. On the one hand, this is to the benefit of the designer; simultaneously, it may make some solutions top-heavy or it may limit the flexibility of the design process. As an example, many mainstream CAD software have displayed this incessant absorption of functionality that is related to the core of the software. As a consequence, using specifics (e.g. features or parametric links) related to the software can easily jeopardise interoperability between systems and tools and can also introduce multi-interpretability (e.g. by having both design and manufacturing features in the same parametric part) [169].

Returning to the four atomic actions that are mentioned above, they are the 'objective' activities that together allow designers to perform 'subjective' tasks at a higher level of aggregation in the design cycle. In this respect, 'subjective' does not directly refer to the designer having a biased viewpoint, it rather means that – in the context of a design cycle – no activity can be seen as separate from all other activities. Therefore, no stakeholder involved can distinguish the object of the activity from its context [161]. What is more, the 'subjective' activities are actually the activities that designers can constructively use in their projects. Examples are: analyse, underpin, search, validate, simulate, scout, ensure, instigate and decide.

As mentioned before, 'decide' is a special item in this list; it actually is the interface between the items in this list and the 'objective' activities. In every step in the design cycle, the underlying 'objective' activities are available to actualise the evolvement of the product definition by a set of interrelated decisions (see also Fig. 7). These linked decisions not only form the 'guiding motif' of a design cycle, it also brings together all stakeholders or actors in that cycle and even in the overlying development cycle or supply chain. The so-called 'actor network' that depicts all relations [145], gives insight in how the context can influence individual activities or decisions, allowing designers to constructively employ connections. Without that overview, connections usually contribute to the complexity of a situation.

Bringing together the individual activities and clusterings thereof, a generic step model of design team activities results [228] that is instrumental in positioning tools and techniques in the efforts of the designer (see Fig. 8). In this model, it is evident how the separation between 'diverging' and 'converging' efforts of designers are reflected.

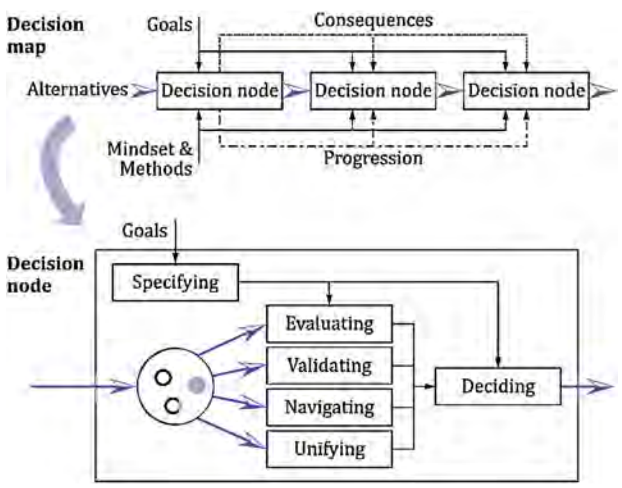

Fig. 7. Generic step model of design team activities.
Redrawn after [101].

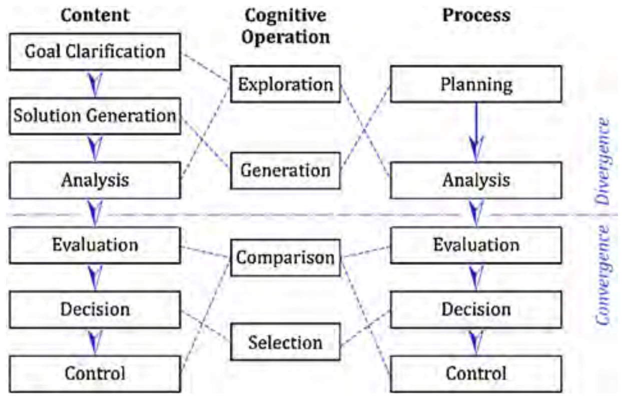

Fig. 8. Generic step model of design team activities.
Adapted from [228].

5.6. Direct versus indirect tools and techniques

Next to diverging and converging working methods in design cycles, there is also a clear distinction between direct and indirect activities in design cycle. Obviously, that same distinction is applicable for tools and techniques. Direct tools and techniques constructively contribute to the design cycle, underpinning activities like concept generation or selection of alternatives. Indirect tools and techniques relate more to collateral (yet essential) operations, e.g. related to embedding, recording or communicating.

5.7. Universal tool characteristics

Next to explaining the working and effects of tools and techniques, many attempts have been made to capture the meaning of tools in terms of characteristics that are – allegedly – independent of the substantive perspective as presented in the previous sections. One of these approaches is based on extensive empirical research based on a survey measuring "designer attitudes towards the character of the tools they use to support practice" [217]. The result (also based on a.o. [64,130]) is a set of so-called universal design characteristics (UDC), giving the characteristics, descriptors and related terms (see Table 1).

Table 1
Universal design characteristics.

UDC	Descriptor	Reference	Terms
Mode of communication	How the design tool supports communication of design ideas to others. How the design tool supports self-reflection and the emergence of design ideas.	Dorta [64] Schön [214] Goldschmidt [91] Jonson [130]	Self-reflective mode Representation, analysis, emergence Dialogue with self I-representations
Levels of ambiguity	To what extent the design tool supports the more ambiguous embodiment of design ideas To what extent the design tool supports the more unambiguous embodiment of design ideas.	Goldschmidt [90,91] Goel [89] Visser [249]	Unstructured nature Ambiguity/density Unspecific
Trans-formational ability	To what extent the design tool supports movement from one design idea to a new idea; horizontal transformations. To what extent the design tool supports movement from one idea to a variation of the same idea; vertical transformations.	Goel [89] Visser [249]	Mode of transformation Duplicate, add, detail, concretise, modify, revolutionise
Level of detail	To what extent the design tool supports a high or low level of specific detail in the embodiment of ideas. To what extent the design tool supports an overall or artistic impression of general detail in the embodiment of ideas.	Brereton [26] Visser [249] Goldschmidt [90,91]	Different kinds of information available. Precision Less/more specific
Level of commitment	How the design tool communicates a higher or lowel level of commitment to design ideas.	Goel [89] Pipes [199] Tovey [238]	Crystallisation/completeness More committed Uncommitted/more committed

Redrawn after [217].

6. Use of tools and techniques

In all approaches described in Section 5, it is remarkable to see how, almost implicitly and without further consideration, the use of tools and techniques is directly coupled with the activities in the design cycle. This makes all clustering attempts quite complex and extensive. Moreover, such clusterings are not necessarily indicative for designers in their practical work.

At the same time, the link between tools and activities is a natural one, given the customary development of tools.

6.1. Development and evolvement of tools & techniques

In a certain sense, the coming about of a technique or tool in design cycles is the direct consequence of the predilection of designers for efficiency and reproducibility. After all, reproducibility is, in many cases, an apparent means to achieve more efficiency. At the same time, the focus on efficiency is again a strong indication that the effectiveness of a tool or technique is at the appraisal of the designer or the design team. The difference between 'doing the things right' and 'doing the right things' becomes very clear here: the designers' expertise and creativity are decisive in selecting which activities to address with which tools and techniques; using tools and techniques can improve the way in which 'things are done'.

In reconstructing how tools and techniques become identifiable and individual entities, the start obviously lies with the activities of the designer. This designer either recognises a reiteration of work, or a situation in which mere mental abilities are inadequate. Especially in situations with routine work, the designer or design team will tend to standardise their approach. In addition, when an innovative idea or approach is instrumental or decisive in how a certain activity is executed, a designer will be triggered to capture that working method. In both cases, discerning the added value of the resulting working method is the first step towards a solution that is meaningful in design cycles. Many of such working methods are contributory to specific designers in a specific context. However, from a rather basic beginning, some working methods grow to have impact in wider forms of co-operation. At that point, an institutionalised working method is regarded as a technique (also see the definitions in Section 4). Many of such techniques are not purely mental models; more often than not, they are dependent on instruments that give practical substance to their application. If depicted or implemented along established lines, a tool can be effected that fulfils this role. Furthermore, the more a technique can be institutionalised and formalised, the more activities related to a technique actually become well-defined routine work and can become part of the tool. Usually, a technique and tool conjointly evolve until a certain maturity is achieved; from there, expertise on the technique and tool can be published and disseminated. From that point, the tool can and will become part of the overall network of tools and systems that underpin the activities of the designer, conceivably in the context of a design method [105].

The traditional Bill of Materials (BOM) is a quite representative illustration of such an evolution. Initially, the BOM was a simple list of components. As it was included on assembly drawings, its completion coincided with the verification of the drawing. Gradually, however, it advanced into a more independent list of components, allowing for e.g. production ordering by IT-tools. With the emergence of PDM systems, the BOM, as a representation of the underlying structure of a product, can even precede the actual definition of geometry. Correspondingly, the role, impact and usage of many tools/techniques related to managing the BOM evolved according to the environment in which they are used.

6.2. Formal positioning of design decisions

From the way in which techniques and tools habitually come into being, there is a clear causal connection between designers' activities and the 'raison d'être' of techniques and tools. However, as the clusterings in Section 5 do not provide an encompassing and decisive way to understand the ways in which tools and techniques can be employed, a more abstract approach is chosen here. After all, not only the relation between activities and techniques is clear, also the relation between design decisions and techniques is practical.

Therefore, a decision in the design cycle is used as the basic starting point. While taking into account all viewpoints on decision-making and respecting the crucial role design decisions have in the evolvement of the product definition and – with that – on the design cycle, a basic building block is constructed (see Fig. 9). It is loosely based on the SADT and IDEFØ standards [158,181], providing structured insights in how the contributors to decision-making co-operate. In this figure, the core is any distinct activity; as is the case according to SADT, such an activity can be recursive. In other words,

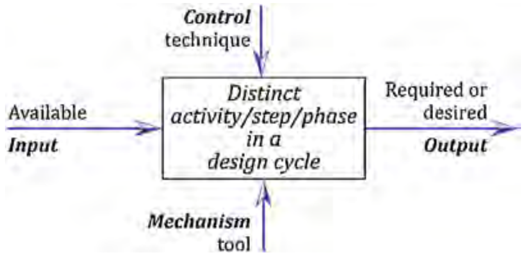

Fig. 9. SADT based representation of activities in a design cycle.

an activity can consist of activities, resulting in an independency of the level of aggregation in the design cycle.

This depiction is in line with the definitions in Section 5; moreover, it gives the opportunity to address the application of tools and techniques in design activities from a slightly higher level of aggregation. From that level, the aspects of using tools and techniques can be described, resulting in a more generic manner of assessing their employment. In effect, here, the characterisation of tools and techniques is decoupled from the specific activities that they initially apply to.

6.3. Aspects of using tools and techniques

From the representation in Fig. 9, an attempt can be made to build a network of interrelated activities. However, without further delineations, constraints and objectives this is a mission impossible [145]. The reason for this is that the connections between all activities may be visible, but that the denotation of the connections is bound to be unclear and incomplete. Therefore, the resulting picture may be informative, yet its practicability is limited.

Below, the most encountered aspects, without claiming completeness, are presented in two groups; the first group lists the aspects that stem from the design project the tool/technique is used in; the second group renders the characteristics that are inherent to the tool/technique itself.

Aspects related to the project

- **Goal:** Every tool/technique should be used because it adds value to a design project as a whole. The envisaged added value can be expressed in the goal of using a tool/technique, in which constraints, functionality, complexity and desired outcome play important roles [180,191]. Moreover, the value that is actually added must justify the cost, time and efforts spent on the usage of the tool/technique. Unfortunately, all too often, this compromise is not made explicit, resulting in routine application of a 'standard' series of tools/techniques [117]. Making the goal explicit, i.e. defining the desired end state of using a tool/technique, adds structure, transparency and critical assessment of implementations and outcomes of tool/technique usage.
- **Phase:** Depending on the phase in which a tool/technique is used, the begin state that is available may vary significantly. For example, in conceptual design, the notion 'strength analysis' has different implications than in the detail design phase [154]. The phasing relates to the quality, certitude and completeness of the available input, but consequently also to the quality and level of detail of the projected outcome. Moreover, the time and efforts that can be allotted to using a tool/technique generally depends on the phase, where a balance between reliability of the outcome and the resources spent is required.
- **Team composition:** The composition of the design team can have consequential impact on the project as a whole (see Fig. 4) [142,207,263]. This concerns the type and level of expertise available, but also the sheer size of the team. The role of tools/techniques in a project has to assimilate accordingly: team composition determines if tools/techniques are employed as in-depth providers of expertise or that they rather aim to facilitate communication and information sharing in the team [206]. Additionally, they can either complement expertise in the team

or they can allow for underpinning and strengthening of existing expertise and experience.

- **Constraints:** No matter how purposeful and effective a tool/technique is, hardly ever will it be possible to exploit its functionality to its fullest extent. As with all activities that require investments in time or cost, the freedom to operate is confined [252]. In other words, the usage of a tool/technique is constrained by the time available, determined either by available lead-time or by time allotted. Obviously, also restrictions related to the available resources (ranging from people to hardware) apply. Moreover, the type and amount of risk (either technical or commercial) that is involved will certainly impose constraints on the way in which a tool/technique is selected, implemented, contextualised as well as on the way in which the outcomes are integrated in the overall project.
- **Complexity:** Even for the development of simple products, the project can be complex; for example because of involvement of external organisations like legal experts, approval authorities or independent test facilities. Here, complexity of using a tool/technique is related to [99] the sheer number of variables (complicacy), time-dependency of those variables (dynamics), the (in)visibility of a subset of the variables (opacity) and the fact that variables can be interrelated (dependency). Next to these, the most relevant contributor to the complexity of a project might be striving for the achievement of multiple, often conflicting goals simultaneously (polytelie [68]).
- **Strategic contribution:** Habitually, a tool/technique is employed in more than one project. Consequently, its usage is geared to the 'average' project. In addition, the implementation and experience may be biased by those other projects and by the company strategy. On the other hand, application of a tool/technique in an individual project may also contribute to the strategy and experience in an organisation.

Aspects inherent to the tool/technique

- **Begin state**: Every tool/technique requires a certain input; if this input is not available, usage of the tool/technique is purposeless or it will render incomplete or unreliable outcomes. This input may refer to the type or amount of information required, to the quality of the information, but also to the prerequisites (ranging from hardware to training) for using the tool/technique. Assessment of the appropriateness of the begin state is mainly based on experience, as obtaining a feasibility study on if and how the desired end state can be reached is not only dependent on the tool/technique, but also on the product under development and the status of the project and its evolvement. Consequently, the connection between the project and the tool/technique depends on the alignment between the begin state and the project progress. More often than not, the project in itself is leading, whereas it could be more purposeful to explicitly impose constraints on that progress from the begin state that is required to start using important tools/techniques.
- **End state**: The reason for using a tool/technique in a design cycle is the fact that the outcome makes an adequate contribution to the product definition, better underpins the product definition, or makes that definition more complete. As such, the Δ-state is the bridge between the begin state and end state. The desired or required end state can be depicted as a requirement specification for the employment of the tool/technique. Depending on the type of tool/technique, the processes involved can start from either side: in case of a brainstorm, the begin state is clear, and the possible outcomes can only be envisaged, leading to an 'open' process, in which the course of action is the means of control. On other occasions (e.g. for finite element analyses), there is a better delineated specification of the outcome, from which a 'closed' process results that can be controlled by the reliability of the outcome.
- **Functionality:** The employment of a tool/technique is justified by its function. In a sense, the functionality determines the Δ-state between the begin state and end state; it therefore causes or facilitates the evolvement of the design cycle [154]. However, in many cases, the required functionality and the functionality provided will not exactly match. As a result, choosing to use an existing tool/technique might be a compromise to the functionality that is specifically required. Additionally, functionality that is available in the 'set' of tools/techniques will bias working methods and even the course of design trajectories.
- **Equipment (alternatives)**: Although equipment requirements may not exceed paper and pencil, other tools/techniques may require more sophisticated means for execution. Some software tools impose quite some requirements on e.g. processing power or storage capacity. Even more, Virtual (or Augmented) Reality tools may rely on the availability of all kinds of very specific hardware [15,183] (e.g. haptic devices [96,114] or even caves [148]); although more flexible, also the employment of synthetic environments [152,172] requires considerable consideration. With this, equipment is not merely an out-of-pocket cost in using a tool/technique; two other aspects are relevant in this respect. Firstly, the effectivity and efficiency of using a tool/technique can directly be related to the equipment selected; i.e. selecting an equipment alternative may influence the quality of the outcome in a non-linear manner. Secondly, for expensive equipment, the selection of tools/techniques over multiple projects can have a strategic impact: equipment may be implemented based on multiple requests, but availability of equipment may also bias selection and employment of tools/techniques.
- **Cost:** The direct cost for using a tool/technique is related to labour cost, equipment usage and consumables. Indirect costs relate to, for example, the availability of equipment, licencing and in (building) the expertise to use the tool/technique/equipment combination. Although difficult to address in cost estimations for a specific project, usually the indirect costs exceed the direct costs by far. From this perspective, employing a tool/technique often seems relatively economical, yet having the tool/technique readily available may involve consequential expenditures that are hardly visible in a specific project.
- **Time to execute:** The time required to execute a tool/technique is often relatively easy to measure; it is, however, much more difficult to determine the time that can or should be dedicated to that same execution. This is related to the time available (deadlines), the cost of using the tool/equipment for a period of time, but mainly to the, often non-linear, relation between the time invested and the quality of the outcome that is obtained. Additionally, the accuracy of estimations for time spent varies considerably. For example, the time required for a finite element analysis may be predicted fairly accurately, whereas the time prediction for a purposeful brainstorming session may be less precise.
- **Implementation time:** As mentioned, a specific project will focus on employing a tool/technique, and any effort related to making that tool/technique available is seen as supplemental work or as a supraproject (i.e. tactical or strategic) task. This does imply that adequate integration of a tool/technique in a company may require more strategic involvement than can be justified from one specific project. Consequentially, such implementation trajectories may impose quite some overhead on all projects involved. Depending on the business strategy, this may engender a rather pragmatic attitude in specific project, causing a tool/technique to not be used to its fullest extent. To mention one example: for carrying over project results to subsequent projects, many tools are available; yet, hardly any project leader encourages spending time on capturing, formalising and evaluating project results and experiences – despite the awareness that it would be a strategic benefit.
- **Installation time**: Whereas the implementation time focuses on making the functionality of a tool/technique available, the installation time addresses the time and efforts required to set-up the environment in a way that allows for adequate usage of

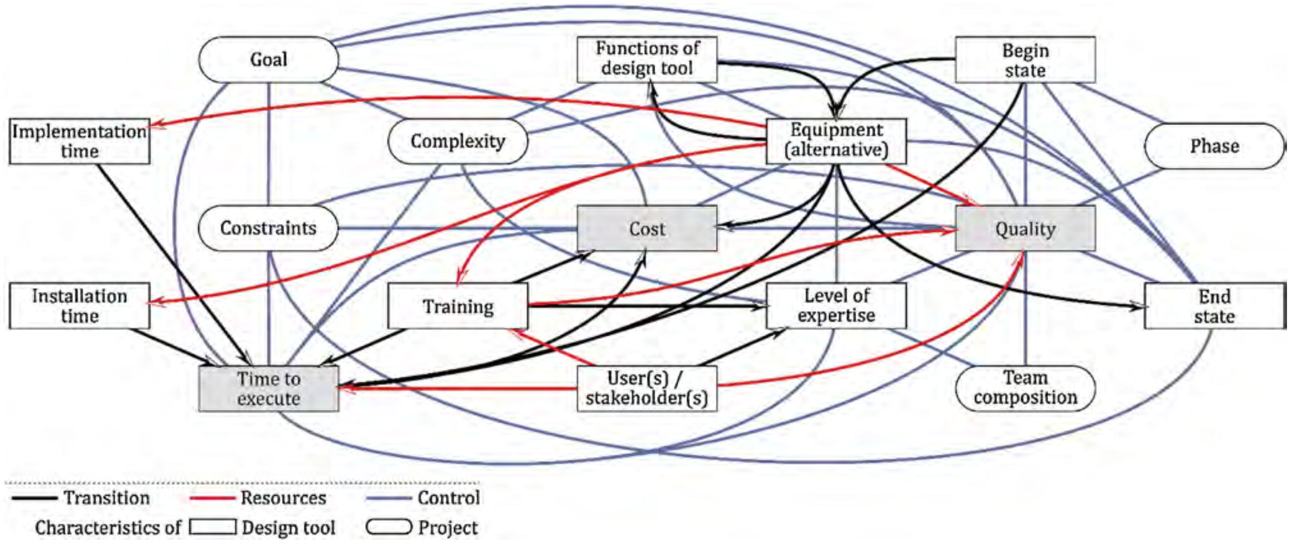

Fig. 10. Aspects of using tools and techniques.

the tool/technique. Again, for a brainstorming session this may seem futile (albeit getting all required stakeholders in the same room can be challenging enough; with technological solutions this may be easier [50], yet the installation will take more time), but configuring a Virtual or Augmented Reality environment or a Synthetic Environment for a specific project most certainly requires considerable efforts [171,183]. In comparing this to production environments: even if the equipment is available, the process planning, production planning as well as set-up times take considerable energy.

- **Stakeholders:** The functionality of tools/techniques can only be unlocked if the appropriate set of stakeholders is part of the environment. Much of the argumentation in this respect is obvious, but when it comes to, for example, using tools/techniques to integrate (end) users in the design process, many pitfalls may be encountered [170,176]. Also in establishing requirement specifications [173] and in decision-making [51], integrating the appropriate type and amount of stakeholders is non-trivial.
- **Level of expertise:** In addition to the type and number of stakeholders, the capabilities of the stakeholders are relevant. Setting aside the fact that some approaches have their own qualifications or certifications (C2C [150], TRIZ [120], Lean six sigma [233]), any tool or technique needs skilled operators. Skills in this respect are twofold: both organisational and concerning content (see also Section 9). As a metaphor, being able to drive a car differs from understanding how a car works. In other words, the value of the tool must be understood separately from its embedding in design cycles. When (end) users are involved as stakeholders, another aspect becomes relevant as well: the more an (end) user is involved in the process, the more he or she will understand of the design cycle itself. The resulting bias may hamper the process, as the 'casual' user grows into a 'trained' user. In this case, stakeholder expertise can have an explicit upper threshold for (end) users, where other stakeholders implicitly aim at growing their expertise.
- **Training:** The level of expertise is closely related to the experience a stakeholder has with using (specific) tools/techniques. More often than not, this experience is, for the most part, obtained while employing the tool/technique. Formal training usually gives an explicit start, but actual familiarisation is a consequence of putting the shoulder to the wheel. This implies that effectivity and efficiency of employing tools/techniques can vary considerably for different stakeholders. Consequently, training levels can have a significant impact on installation time, time to execute, end state and therefore also on cost. To avoid negative impact on the tool/technique itself, the certification mentioned is used as a measurement of the training level. However, for the large majority of tools, the required level of training and the impact of the training level are far from clear. At the same time, there is a tendency to regard tools/techniques as infallible and definite solution providers, instead of resources in the hands of craftsmen. Irrespective of the validity of this viewpoint, it most certainly diverts from the actual design cycle.
- **Quality:** Where quality can be objective and subjective at the same time [200], the different perspectives from Fig. 4 prevent from any unequivocal pronouncement on the use of a tool/technique. For one specific project, the impact and denotation of a tool/technique is different than for a company or a (group of) persons. At first sight, this may render the aspect quality rather impracticable. However, it can also be considered the linking pin between different perspectives, i.e. the aspect that connects strategic attention for a tool/technique to its tactical and operation use.

6.4. Relations between aspects of using tools and techniques

This set of aspects is not a checklist or a blueprint for tool selection. Rather, it is the basis to for understanding how tools, activities and decisions interrelate. To adequately address those interrelations the basic scheme of Fig. 9 is used, but now with these aspects as the core. Again, without claiming completeness, a network is generated from these aspects. In other words, the black lines reflect connections from input to output, the red lines are resources or mechanisms and the blue lines are controls. At first sight, these mutually dependent representations in Fig. 10 merely seem to give rise to complexity. However, using the approach of Fig. 9, it actually disentangles activities, tools/techniques and aspects of the usage thereof.

In this, the resulting overview emerges organically from the variety of input information used. Therefore, the number of relations is informative as concerns the relative importance of aspects. From Fig. 10, it is clear that a significant role is reserved for the usual suspects: costs, quality and time (to execute). At the same time, they can be related to the other aspects that play a role.

7. Selection of tools and techniques

Selection of tools and techniques can be compared to a design decision. The selection of the tool or technique will, in itself, influence the entire process as well as its outcome. Moreover, this selection often has to be made when the design problem is not even clear, under conditions where multiple stakeholders are involved and many criteria simultaneously play a role. Without recursively focusing on decision-making in design here, it is relevant to discern two different ways to reach such decisions [221]:

- Process-based evaluation; focuses on 'how' the ideation happens, i.e. the structure of the process.
- Outcome-based evaluation; focuses on the outcome of the process, i.e. the quality of the outcome achieved.

However, unlike in 'standard' decision-making, in the selection of tools and techniques not all alternatives are readily available to choose from. First of all, implementation of a specific tool/technique combination might not only influence the development cycle under consideration, it can have (strategic) consequences for other projects, as well as for the company as a whole. What is more, it can be argued that in implementing tools and techniques one cannot speak of selection as such [184]; there are not many tools that can be bought 'off the shelf' and be introduced without further notice. In every environment, they have to be implemented in a structured and controlled manner, while explicitly paying attention to the way in which the designer's work might be influenced. This process, sometimes referred to as the "tools acquisition process" [58], has even more influence for large companies with many departments and design teams. Other complicating factors are for example decentralisation of the company, designers with different backgrounds or expertise, experience and habituation as well as conflicting stakeholder interests. In case of introducing new systems in a company (i.e. CAD, ERP or PDM systems, see Section 4), well-nigh all these aspects are involved simultaneously. This explains why such an implementation trajectory may span multiple years and can be critical for the operational management of a company (see e.g. [23]). The selection of tools and techniques becomes even more critical if co-operation between organisations (possibly decentralised/international) is required. This involves agreement on existing tools/techniques, or (joint) commitment for the development thereof. Underestimating the importance of this alignment can directly result in significant delays and cost overruns during the integration phase of the product. Moreover, selecting shared yet non-aligned practises can dramatically reduce the effectivity and efficiency of the design phase in all companies involved.

Such considerations present companies with a problem that has two faces: on the one hand, pragmatic and agile efficiency is most useful when aiming at solving a design problem in operational mode. On the other hand, a holistic approach might clearly be to the benefit of more projects or to a larger part of the company. However, such a holistic approach will probably decelerate the design project that first identified the need for a tool/technique. Moreover, the scope of an all-in-one approach is often too big to be an easy success, due to organisational complexities.

Often, decomposition approaches can help to solve such paradoxes. However, a precondition for that is that the tool selection process follows a hierarchical decision flow. From the argumentation in the above, it will be clear that this is usually not the case. This is all the more true if company strategy influences that flow. In other words, selection of tools is indeed comparable to making design decisions, as it is no longer about the handling of standalone optimisation problems, but rather about joint optimisation of a number of individual problems (see e.g. [128]).

In selecting tools/techniques, it is obvious that the success of a tool has lots to do with the choice of an appropriate tool [129]. This appropriateness of tools/techniques is often related to their functionality, rather than to the other aspects mentioned in Section 6.3. Consequentially, it is not uncommon that, from this selection point of view, tools/techniques are seen as mere building blocks of the overall design framework. In assuming that this is a valid approach, selection can be done by means of, for example, morphological charts [129]. Another approach is to separate 'designing the design process' from 'selection of tools' [47], from which the conclusion is that only in a few situations a totally 'prefabricated' strategy can be a good option. Often, designers follow their own approaches in devising a solution strategy and adjoining tools/techniques; simultaneously this may lead to less overview in a project or amongst members of a design team. If designers indeed go 'shopping' for tools/techniques, a catalogue-concept could be applied [117]. They can purposefully select a tool/technique, if details and descriptions of all aspects of using them are available. More often than not, establishing such a catalogue is a less feasible endeavour than expected. Moreover, this approach may work for 'quick-and-dirty' tools/techniques, but for tools/techniques that have serious constraints as concerns for example investment, installation time, cost etc. selection is much more than singling out a solution in a catalogue. This is all the more true in realising that the understanding of a problem may depend on the degree of knowledge of the available solutions [235].

7.1. Requirement specifications; from stated purpose to scenarios

In comparing the selection of tools and techniques to design problems, it is more than probable that the same flaws that are often encountered in product design affect the selection process. A typical flaw is the lack of adequate specification of the actual design problem at hand. It will immediately be clear that insufficient specification of the requirements for a tool/technique can have far-reaching consequences with significant loss of time and resources while frustrating everyone involved.

In practice this means that, all too often, the basic idea of where a tool/technique should be instrumental is clear enough, but that further settlement is limited to the mere technical specification. This implies that the usability of the tool is reduced to its quantifiable meta-data (like price, computer platform and number of users/licences), but that the meaning and added value disappears from sight.

It would be much better if functional specifications would be used to express e.g. what the tool/technique should be capable of, how flexible and scalable it has to be and what reliability it should bring under which conditions. The advantage of such specifications is that they can be tested by dedicated tests or case studies. From this, implementation and training can be simplified considerably as well.

The best option, however, would be to start from a scenario [173] in which the future use of a tool/technique is depicted. Such a way of working focuses on the actual aim and denotation of the tool/technique, from which the other types of specifications can be deduced. In addition, scenarios are helpful in training, but especially in understanding the (strategic) consequences of a tool/technique.

7.2. Affordance of tools and techniques

The word affordance was coined to refer to the actionable properties between the world and an actor [86]. Here, affordances are relationships. They exist naturally: they do not have to be visible, known, or desirable. In the context of design objects, the notion shifts to understanding how a user manages in a world of tens of thousands of objects [189], without being trained in the contact with the objects. Essentially, the appearance of the object can provide the critical clues required for its proper operation [247]. Literature gives many examples of how a tool (like a hammer) can be perceived in different ways (e.g. [12,260]). Obviously, the same yields true for tools/techniques as used by designers and design teams. These tools/techniques may be brimming with potential contributions to the design cycle, but to exploit such offerings to their fullest extent, tools/techniques need to expose all capabilities and capacities in such a way that designers see them as a continuation of the activities in the design project and its context. Given the fact that many tools and techniques arise from a specific background and context in a bottom-up manner, this is far from obvious. With all aspects that play a role in the design context, it can be arduous to match optimal tool/technique usage to an environment. It at least requires that conformance with all aspects as mentioned in Section 6.3 and Fig. 10 are addressed. This also assumes that the usage of tools/techniques can be explicitly embedded in a changing context, where prospective tool users can assess contentual and organisational implications, while paying sufficient attention to e.g. planning or stakeholder buy-in [256].

Moreover, there are many uncertainties and ambiguities inherent in the usage of tools/techniques themselves [218]. How will the tool/technique communicate ideas? [64]. How flawless or equivocal do these communications need to be? [89,214] Is the tool usage aimed at generating a variety of ideas or the progression of a few? [89,249] What is the level of detail that is required? [26] How much commitment to an idea will the use of the tool communicate? Obviously, neglecting to consider the character of the tool/technique and how this influences practice, may lead to miscommunication, unsuitable representation of design ideas and early fixation [89].

Obviously, the deployment of tools/techniques is different for large companies as compared to small and medium enterprises (SME's). Without putting aside the complexities encountered in an SME, smaller companies usually have ample flexibility in adopting new tools/techniques, they often do not develop a wide portfolio of techniques themselves and they are limited in tool/technique usage mainly by financial reasons. For large companies, the two main stakeholders that are concerned with the operational evolution of design tools inside the company are the design specialists themselves and IT facilitators. Although they share a common target – being the overall increase of the company's efficiency and effectivity – it is not a given that they go around together in achieving that target. An important cause for this is the fact that the overall efficiency of the end-to-end design process of a complex product is well-nigh impossible to determine [70,219]. All too often, this results in establishing local metrics. Designers estimate the benefits of the implementation of a new tool by a projected reduction of the time spend to perform a task. Alternatively, IT teams are more sensitive to the cost of software licence, maintenance costs, and obsolescence management [212]. Any successful implementation of new tools and techniques will require a dedicated project organisation in order to identify all the stakes and to make final trade-offs that will contribute to the added value at company level. Benefits have to be clear enough to get the agreement of all users and managers to allow for exceptional IT expenses or recurrent cost increases. In this, the motivation for managers can only stem from reductions of overall development cost, lead-time, risks or workforce.

8. Uncertainty and ambiguity in using tools and techniques

By definition, everything that is 'not exactly known or decided, not definite or fixed' is uncertain [3]. For product designers, such a definition is hardly instrumental, as they unremittingly struggle to make the appropriate decisions that separate them from the envisaged product definition [152]. There are many things that obstruct a design team in making a specific decision. The most obvious is a lack of information. However, equally important is the observation that design teams establish requirements while attempting to fulfil them at the same time (see also Section 3 and [151]).

Here, the notions uncertainty and ambiguity become relevant, as they address different causes for stakeholders to have non-concordant and irreconcilable views. Research on (especially technical) problem solving, has addressed (already quite early) the effects of ambiguity and/or uncertainty on the problem-solving process [160,232], the interplay between uncertainty/ambiguity and organisation structure [93,146,147], and the need for different communication channels under different uncertainty/ambiguity conditions [9,240,241]. Most empirical work on technical problem solving has two characteristics in common [215]. First, no explicit distinction between uncertainty and ambiguity is made; the two concepts are used as if they were interchangeable although the literature provides several frameworks to distinguish between them [56,197,255,259]. Second, uncertainty and ambiguity are considered exogenously given variables that managers must react on.

8.1. Uncertainty

Uncertainty can lead to confusion, but it also provides the freedom to employ tools/techniques in creative problem solving. A precondition for this to be true is that the uncertainty is manageable: it must be credible that the uncertainty is 'closed' in the sense that it concerns a lack of knowledge of facts that are indeed obtainable. That is, a designer may be uncertain about whether a new design will work, but this uncertainty can be decreased with further analysis and experimentation. However, this is often hampered by the limited time/resources available to product developers.

Decreasing or removing uncertainties is often a matter of routine work, by generating and evaluating alternatives. In terms of tools/techniques, this stresses the relationship between uncertainties and the requirement specifications. Both address solution spaces that are confined, where more information can lead to better, more accurate or more underpinned solutions. Here, a better understanding of the solution space can directly improve decision-making [56]. In employing for example 'what-if' design [62,154], 'performance indicators' for the product definition can be determined without distracting product designers from their core activities. Another way to routinely utilise tools is to check implicit consequences of decisions in the background, i.e. to generate warnings if constraints are violated by decisions that may seem unrelated. In both cases, it is important not to rely on the capabilities of tools to independently influence the design process: where product designers may not have a complete overview, such reliance in the valuation of dependencies can only give illusory certainty.

8.2. Ambiguity

Often, product designers feel confident in counteracting the uncertainties they perceive, whilst purposefully distributing part of the available resources/time over the uncertainties that call for elucidation. However, more often than not, indistinctnesses are encountered that cannot be dispelled, irrespective of the amount of information available. This is the case for situations where it is even not obvious or predictable which entities/uncertainties play a role [152]. This type of indistinctness is referred to as ambiguity. In product design, ambiguity relates to the origin of uncertainty; it addresses the inherent insecurities of e.g. the subjectivity with which certain aspects in a design (are assumed to) prevail over others. An important example is 'the voice of the customer'. As all market research builds on sets of hypotheses, the research in itself will influence the answers. Moreover, answers are quantified against that set of hypotheses; therefore, this type of research usually is about finding indicative solution directions.

Ambiguity can be described as 'second order uncertainty', where there is uncertainty even about the definitions of uncertain states or outcomes. It therefore relates to human definitions and concepts, rather than objective facts of nature. Obviously, this is inherent to product design. Given the engineering approach towards uncertainty, product developers inherently attempt to capture ambiguity and reduce it into uncertainty. The reason for this is that designers, but mainly engineers, think they have the adequate tools to fight uncertainty. However, ambiguity is inherently different from uncertainty in the sense that uncertainty aims at answering a question where ambiguity is about determining what the question is.

8.3. Uncertainty, ambiguity and determinism

In the early stages of problem definition, there is only a broad understanding of the requirement specification. Sometimes, it is very difficult to characterise the possible users and use cases of a product. Moreover, in both the problem definition phase and in the solution phase of the design process there usually are many stakeholders. As a consequence, the set of requirements to start with is nearly always incomplete and even inconsistent. In the specification of product requirements, even those of low complexity, designers have to cope with the fact that the set of requirements remains variable during the process. New requirements may arise and existing ones might changed or be dropped. Building a product design on such a potentially unsettled basis involves risks. The main initiator of these risks is that product designers tend to focus on the solution space as quickly as possible, whereas paying ample attention to the problem definition phase is often subordinated. Exploring this problem definition involves multi-stakeholder objectives synchronisation. Subsequently, possible product use scenarios should be evaluated and alternative solution principles should be tested. Because the production of physical prototypes is generally costly and time consuming, testing is preferably done in virtual worlds where possible. Virtual environments for the definition and management of requirements as well as virtual test beds are becoming feasible and affordable [50]. They will support the design methods and tools for the future [168,172]. At the same time, designers have to rely more on a posteriori assessment of their concepts; current simulation tools/techniques are limited in e.g. the actual generation of feasible geometry; for example because of non-linear physical phenomena.

The application of virtual or synthetic environments prevents the traditional engineer from immediately attempting to nullify uncertainties and ambiguities. After all, in applying the right tools/techniques, both types of indefiniteness can become valuable means to understand the design process, the project at hand and the stakeholders involved. Here, different approaches are possible. For the earlier phases of product design, ambiguities can be identified and addressed by studying scenarios in synthetic environments. Scenarios aim to identify all relevant influences on product development cycles, while achieving synthesis between information, resources and control mechanisms to reach adequate solutions. As such, scenarios depict ‘possible futures’, including assumptions and predictions, but also prognoses on how the product under design will influence the environment in which it will be used [52]. Therefore, scenarios explicitly incorporate contingencies and make pronouncements on aspects that, by definition, are not verifiable or assessable, yet can be agreed upon. This approach may attract criticism, although it is exactly what product designers continuously do, albeit implicitly. Making such assumptions explicit strongly contributes to the design rationale, as design decisions can be re-assessed later in the project, or in subsequent projects. This is instrumental in determining e.g. the robustness of a design solution space [56]. This robustness in itself is challenged by the fact that, increasingly, hardly any solution is seen as the ‘final’ solution, but rather as the ‘feasible’ solution that always allows for improvements [215]. This implies that any state of the product definition represents a temporal status quo; any change to this situation will, in itself, reintroduce ambiguity and uncertainty in the process. This by no means implies that the product design process is an uncontrollable game of chances. It does imply that it is nearly impossible to make exactly the same decision twice, as the environment and conditions that underpinned the decision will have changed, e.g. under influence of other decisions. In other words, product design becomes a process that is no longer deterministic.

Traditionally, engineering approaches are assumed deterministic in nature; identical questions result in identical answers. As such, a deterministic system is a conceptual model that renders its outcome completely based on causality. In a deterministic system, every action, or cause, produces a reaction, or effect, and every reaction, in turn, becomes the cause of subsequent reactions [152]. However, given the considerations above, product design more and more withdraws from these deterministic characteristics. Therefore, product designers have to deal with design cycles that no longer adhere to concrete and definite causality. For example, if computer power is used to perform routine work, the identical question may get different answers over time, simply because more or better information to answer them is available, more resources are available to find that information, or increased insight in the overall design project can better direct the process. Moreover, the tools/techniques themselves can be inherent causes of indeterminism. For example, it is impractical and unfeasible to do the same brainstorming twice, as the process itself will influence the input for any next attempt. Product designers are aware of this; therefore, they will purposely use such tools/techniques in a well-balanced manner, adequately contributing to the evolvement of the product definition. Objectively and formally managing such creative processes therefore becomes a sheer impossibility. Attempts to objectify them (in e.g. market research, or capturing the ‘voice of the customer’ [34,82,103,118]) are momentous challenges.

9. Human factors and education

A company has a set of tools at its disposal, but needs prudent and judicious deployment of these tools to render their introduction profitable. After all, the tools in themselves are reactive constituents of development cycles. It is the skill of the person who wields the tool that makes it effective. In a similar manner, a company can pride itself upon the techniques mastered by its employees; this mastery does not evolve the product definition.

In a production metaphor, buying a milling machine or robot is easy compared to its adequate incorporation in the production environment. In other words, even the best tool/technique is not able to substitute for gaps in technical knowledge and expertise. They represent merely one dimension in the design work, forming one of the prerequisites for successful work, together with technical knowledge, experience, talent, ability, perseverance, and other personal properties [117].

In terms of Fig. 10, users, level of expertise and training all have a direct influence on quality, time and cost. Therefore, the user of the tool/technique is inextricably wound up with their effectivity and efficiency. Amongst the preconditions related to this, it at least implies that the users are able to interact with the tools, i.e. understand the benefit, possibilities, demeanour, particularities and limitations but especially the language of the tool/technique. This becomes all the more relevant as the designers co-operate in teams. After all, with the different viewpoints involved in design teams, a common understanding of the tools/techniques that are applied may be as important as the understanding of the design problem itself. This is reflected in any change of design systems or design tools in large companies: the actual installation of the tools hardly takes any time as compared to the time and efforts spend on creating commitment, preparing for changing the working methods and aligning the new system or tool with the company and departmental cultures. Such trajectories may take years, as is exemplified by Daimler’s change from Catia to Siemens NX with all issues involved [23]. The essence of such trajectories usually is in creating shared understanding among all stakeholders – including e.g. suppliers.

Any framework for a design project should therefore pay attention to a shared vocabulary to facilitate communication [137,187]. Even for small teams, it allows designers to sketch (at intellectual level) immediate and consecutive mini-plans on what and how to do the next action, and create awareness of why it should be done that way [57]. Any common framework provides a means to structure knowledge in a uniform manner, enabling easy knowledge access, reproduction, recovering and re-use [68,165]; this is to the benefit of both the current project and for planning, management and execution of future projects [184]. It also forces an understanding, analysis and evaluation of the project on a conceptual level [110]. Thus, in everyday practice, the triad tool/technique/designer upholds the overall knowledge realm in the design team, with a clear tendency to include more knowledge application in the tools. The consequence is that it is important to evaluate the opportunity to evaluate what kind and level of knowledge can be formalised, shared and used in a knowledge management tool [18,258]. This can have a significant positive influence on innovation and design capacity [257].

With regard to training and education, such knowledge initiatives are also relevant, for example to aid in bridging the gap between novice and experienced designers [220] and allow them to effectively work together. In addition, cultural aspects can play a role in this, especially in decentralised product development or remote collaborative work [50,85]. In research and education, such topics are addressed [44–46], although the link with practical situations in industry is difficult to make.

The human factor goes far beyond the designer as (becoming) a trained and skilled operator of tools and efficient executor of techniques. Tools/techniques should facilitate designers in their work, being subordinate to the goal of the design project. As such, they should never hamper that process by imposing constraints on how the project can run, thus frustrating the designers. All too often, tools/techniques become burdens rather than valuable assets, especially if designers have to spend effort in using a tool that does not directly seem to benefit the design project at hand. To prevent this, it is essential that the designers and the design team are in control of how and when which tools/techniques are employed, but that they are also included in discussions on the usage of tools/techniques across projects. That this approach underlines the wilfulness that is seen as typical for designers can only be instrumental in this respect. To mention just one example: designers often have difficulties in understanding the point and necessity of adding metadata to their work; at the same time, they see the benefit of having metadata.

To an increasing extent, non-designers are also becoming part of ideation and design cycles. Relevant examples in the context of mass-customisation [49,72] are co-creation [104,179] and 'voice of the customer' [6,38] in capturing user intent or behaviour [36,231]. Many of these approaches underestimate the difficulties entailed in confronting users explicitly with issues that usually are inherently implicit. In addition, the skills of the untrained user in interacting with a (software) tool while understanding the essence of the technique are often too limited, whereas training them would inadvertently bias the results. To an increasing extent, product designers must be aware of the human factors in co-operating with external stakeholders, of which users are only an example.

More and more, designers have to be creative experts, skilful in selecting and employing appropriate tools with the right participants, in the right phase of the project and an effective and efficient preparation, while doing justice to cultural and intangible influences on the course of that same project. Therefore, designers increasingly withdraw from traditional fields of expertise and become versatile engineers that simultaneously execute the design process and manage it, while amalgamating all different viewpoints involved. This obviously calls for a different way of educating designers; in academia this need is certainly identified, and many initiatives are developed [32,43,55,237].

10. Industrial application

Designers and design teams always do their work in a specific environment and context. Such surroundings not only influence the aim, rationale and starting points of the designers' work, they also have a significant influence on the selection of tools/techniques, their operating modes and their impact on design projects. Given the incredible set of variations in product types, companies and product/market combinations, no enumeration can contribute to meaningful understanding of the position of tools/techniques in industry. Therefore, a generic approach as offered by the Zachman framework [261] is selected to model the application of design tools/techniques in industry.

10.1. The Zachman framework

The Zachman framework (see Fig. 11) is represented in a 6×6 matrix, with connections between the cells indicated [94,95]. It describes architectural information with a number of different subjects along its vertical axis, as it passes through the stages of reification from idea to physical reality. All industrial products have similar architectural perspectives [134]: Scope (boundaries)/Requirements (concepts)/Design (logic)/Plan (physics)/Part (configurations)/Product (instantiations).

Fig. 11. The Zachman framework–Enterprise ontology.

The manifestations of these architectural perspectives determine the types of information described in the framework, being scope contexts, business concepts, system logic, technology physics, tool components and operations instances, as indicated by the row labels to the far right in the framework.

In the top row of the framework, scope contexts identify the architectural items that form part of the architectural description at a strategic level, thereby identifying the boundaries of the architecture. The definition of business concepts, including the relations between them, in the second row defines what certain architectural terms mean in the context of the specific architecture being described. These business concepts form the requirements for the supporting lower architectural levels. In the third row, the design logic of the enterprise is represented, thereby focusing the description of the enterprise architecture on the system level and indicating its internal organisation. The specification of technology physics in the fourth row puts the architecture description on a more technical path, by specifying the technological plan that will be configured to instantiate the enterprise. In the fifth row, the tool components that form the constituent parts of the technological specification are configured to produce the operational instance of the enterprise in the sixth row.

10.1.1. Scope of information in the framework

The scope of information covered by the framework is variable, due to the fact that the underlying logic of the framework can be applied to any object [134]. This means that the framework can be scaled to fit any of the values along the scope dimension of architecture frameworks, including industry sector, organisation, organisational domain, system family and system component. The precise scope of an implementation of the framework is determined by the architectural boundaries identified in the first row, and there is therefore a link between the business information the framework describes and the scope of the rest of the architecture. The columns of the framework provide evidence for comprehensiveness and are labelled "abstractions" that combine to provide the total set of relevant descriptive characteristics of the object. These abstractions are universal and are common to all industrial products [134]. The abstraction columns answer the six basic interrogative questions, being what, how, where, who, when, and why, respectively. The columns correspond to "the universal set of descriptive representations for describing any and all complex industrial products" [134] and are:

- Inventory sets, described in bills of material.
- Process flows, described in functional specifications.
- Distribution networks, described in drawings.
- Responsibility assignments, described in operating instructions.
- Timing cycles, described in timing diagrams.
- Motivation intentions, described in design objectives.

10.1.2. Applying Zachman to the design process in an organisation

As mentioned, design tools/techniques cannot be considered in isolation, and the design process as well as where it fits into an organisation must be the driver. Using a framework such as Zachman thus provides a mechanism that ensures that the design process is considered in a holistic manner. Each tool and design phase can be mapped to a transformation in the framework, and each design tool can be considered in terms of the interrogatives. The challenge, however, is to decide to which extent the application of the Zachman framework is purposeful. After all, the framework in itself is a mere tool, with all characteristics thereof. To put this into perspective, the horizontal dimension contains the interrogatives, and this is a very complete set, that is useful to apply on any level. Considering a design process, these interrogatives can be applied as follows (example on an executive level, see also Fig. 12):

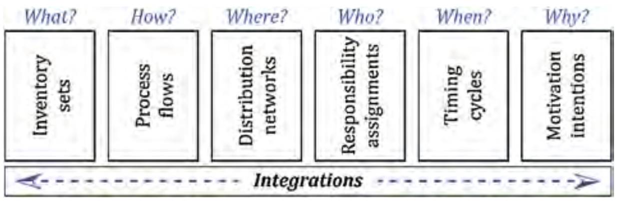

Fig. 12. Interrogatives dimension of the Zachman framework.

- What... types of designs need to be executed?
- How... is the process flow of the design process?
- Where... are aspects of the design executed?
- Who... is responsible for each aspect of the design?
- When... does each aspect or phase of the design happen?
- Why... is this aspect of design required?

The vertical dimension contains the reifications [261] (see Fig. 13), and it is here where an executive perspective at the highest level of each interrogative is transformed into a specific instantiation on a very technical and detail level on the lowest level, with each level adding more detail in each reification context.

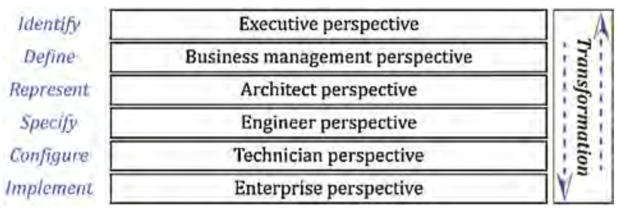

Fig. 13. Transformations in the reification dimension.

The top three levels address the business architecture, while the lower three levels focus on the Information Systems Architecture. Depending on the scope of a design process implementation, the latter three levels are easily overseen as less applicable for design tools/techniques. This may be true from a business perspective, but especially the ways in which these three levels are addressed confront the designer and the design team with the practicability of tools/techniques in their everyday work. Moreover, in recognising that many tools/techniques have a bottom-up background, the framework can be applied to recognise and facilitate organisational changes based on the lower levels of reification. Research on this type of topic is not abundant. This is mainly due to its bottom-up basis and the fact that such a basis might conflict with hierarchical principles often implicitly applied in enterprise architecting. The sheer technological capacity and power embodied by tools/techniques in the hands of capable designers may call for a countermove. Instead of aligning the design process to the implementation stemming from a framework, industrial organisation may be able to more effectively and efficiently exploit their design capabilities by addressing the way in which higher levels of reification can facilitate and give room to the value-adding design works and the tools/techniques that underpin that work.

10.2. Industrial embedding

Given the structuring offered by the Zachman framework, design processes in industrial environments can be purposefully contextualised. Again, any enumeration is inadequate by definition; yet the way in which design tools/techniques are employed, is illustrative of their interrelation with the organisational environment. Many of such relations conform with the descriptions of Section 6.3 and Fig. 10; industrial examples can demonstrate impacts that go beyond the use of the tools/techniques. In this, many different dissections of the design process are possible; one example is shown in Fig. 14 [81,121].

The following sections depict a number of industrial examples of design tools and techniques stemming from an aeronautical design environment. The examples are described according to high-level phasing of the design cycle.

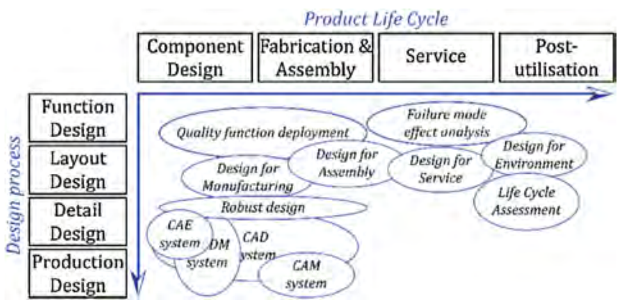

Fig. 14. Schematic depiction of tools/techniques versus design process and product life cycle.
Redrawn after [81].

10.2.1. Pre-design

The designer has to understand the customer needs and has to obtain a general comprehension of the design environment. In this, 'traditional' techniques from value analysis techniques [174] like environment diagram, operational scenarios or use cases are relevant. Such "soft" design techniques are used as input by engineers to envisage solutions. In this, creativity tools (see Section 2) are instrumental. The outcome encompasses e.g. artistic drawings and initial performance simulations; all based on the company expertise and the proprietary techniques and simple (software) tools that stem from that. Uncertainty is a significant aspect here, so scenario thinking prevails over detailed studies.

10.2.2. Functional Design phase

The work of the designer focuses on the functional analysis of the product. Especially for innovative products, the Functional Breakdown Structure (FBS) is a definite act of design. In re-design, the FBS is instrumental in finding design improvements [69]. This result is the backbone of any Quality Function Deployment methods (QFD) [175], or System Engineering [213] practices. The FBS will be also used to perform Functional Hazard Assessment (FuHA) [74]. Conjointly, these approaches aim to establish a first specification of the product.

10.2.3. Conceptual Design

In the design space offered by the specification, the designer – aided by creativity techniques and adjoining problem solving techniques – starts the search for technological solutions [80]. Contradictions in the specifications drive the challenges for designers, where e.g. weight and safety require trade-offs in aircraft design. Any product concept has to answer to the specifications using realistic technological solutions. To capture such solutions, CAD systems/tools can be used, allowing for performance evaluations (based on well-defined geometric data). Analytical techniques or CAE tools aim to evaluate different concepts and allow for accentuating requirement specifications.

10.2.4. Embodiment design

The product concept is selected and elaborated, addressing the simultaneous design of subsystems. Integration checks are based on a digital mock-up (DMU) [167], allowing for systematic zonal analysis [30], to identify geometrical clashes or undesired physical proximity between systems like pressurised oil pipes and electrical wiring. At system level, all components require geometric definition (again by means of CAD systems/tools) and evaluation against the specifications in different domains (mechanical, electrical etc.). A current trend is to rely more and more on virtual simulation and testing [169] to early assess product performance. Tools for FMECA (Failure mode, effects, and criticality analysis) aim to effectively and efficiently identify failure modes for any part of the system. With this, requirement specifications and design targets (e.g. weight, cost) are re-adjusted, requiring design review techniques to ensure the overall project validity [149].

10.2.5. Detailed design

To ensure an unambiguous product definition, the detail design phase aims to fully define all details of (the components and the assembly of) the product. Regularly, such a definition allows for production of the product. Tolerancing activities are employed to guarantee the minimum performance of physical parts of a system. Here, interactions between production and design emerge, addressing e.g. cost and performance trade-offs. The evolvement of tolerancing techniques and standards [126], and the fact that different mathematical approaches are used to perform tolerance evaluation implies that tool selection is related to product characteristics. Such dependencies emphasises that standards used for tolerancing must be agreed upon between design organisation and production organisation in order to avoid dramatic misunderstandings.

For a product design company, usually the underlying backbone for the definition of geometry in detail design is the CAD system. Depending on the type of industry, different vendors dominate the market; in aircraft design, many companies have been using the Dassault Systèmes CATIA software for more than 20 years. This provides an adequate case study for illustrating the impact of a change in a design tool. To mention just a few examples in the evolution from CATIA V4 to V5, the advent of parametric design capacity brought significant advantages at design team level, but at the same time required (re-)definition and (re-)implementation of (company-)specific techniques [169]. Likewise, the ability to create assemblies in the system redefined the notion of assembly itself: it received a geometry-oriented status (engineering bill of materials), whereas traditionally a system or traditional BOM (manufacturing bill-of-materials) approach often prevailed. With this, many specific techniques related to BOM-management, modular product architecture [8] and product(ion) structuring required reconsideration [127]. Consequences of this change reverberate through the entire organisation, influencing e.g. ERP and planning systems. Obviously, efforts required are significant, resulting in change processes with long lead times, configuration management problems and an associated increase of uncertainty [135]. Moreover, in the transition to the new version of the CAD system, more powerful possibilities for DMU became available. Although this gives the design team many new options to assess different facets and life cycle aspect while avoiding building physical mock-ups, this seemingly more detailed DMU in itself does change requirements imposed on design techniques. After all, the DMU can never be more detailed than the current state of the product definition allows for. Together with complexities introduced by configuration management (especially if it is unaligned with DMU), the appropriateness of many analyses techniques is equivocal. Consequently, new techniques, methodologies or customised software have to be developed to exploit the benefits at operational level.

At the same time, the IT environment in which these systems and tools are used is changing rapidly. Especially changes as regards to operating systems and databases can cause a 'simple' CAD version evolution to have a total lead-time of several years with investments of several million euros.

In parallel to the evolution of CAD, the capacity of simulation tools has expanded significantly, driven by changes in hardware and by advancements in mechanical-mathematical modelling. At the engineering level this allows for more accurate system simulations, provided that designers have full control over those simulations. Stated differently: it is not the capacity of the tools that realises the accuracy, it is the way in which designers interact with those tools that allows for efficacious results. As an example: to compute the equivalent Hertz pressure between two components, multiple mathematical schemes can be used. Depending on the geometry of the contact area and the material properties, some mathematical schemes are inappropriate. As a consequence, new simulation features have to be accompanied by a dedicated validation plan by means of additional or updated techniques [169]. The cost of such validation plans can easily exceed the cost of the new simulation tool. This is one of the reasons why these kind of tools have a low penetration rate in industry. Moreover, when establishing a technical validation plan, the IT software and hardware evolution must be taken into account; given the volatility of that evolution, it is nearly impossible to arrive at a situation that is sufficiently stable, while simultaneously vouching for traceability.

11. Problems with tools/techniques

Designers can rely on a vast array of available tools/techniques to support them in their work. Despite this (or infused by this), a lot of ambiguity is encountered. One of the main reasons for this equivocality is the dualist background of tools/techniques: in general, they stem either from academia or from practice.

In the latter case, they are often the result of ingrained habits in a specific environment. Consequently, such tools/techniques are difficult to transfer to different environments. Setting aside the aptitude for different environments, industry is often not inclined to stimulate such transfers. This can be because the possibilities in 'marketing' the tool/technique are simply not recognised or require efforts beyond the interest of the company, because the intellectual property embedded in them prevents the company from exposing them (strategic know-how), or because the company's reputation is not sufficient to actualise and introduce a formal tool/technique [58].

Tools/techniques stemming from an academic background suffer from less practical demerits. Research consistently shows that structured and equivocal use of 'academic' tools/techniques in industry is traditionally poor [11,57,58,88]. Part of the problem is said to be intrinsically related to the poor quality of the tools delivered by researchers, which are generally seen by practitioners as being too theoretical or complicated to understand, while using 'strange' language and being difficult to implement, use and evaluate [58].

In summary, these drawbacks actually state that academia focuses too much on the 'function of the design tool', but oversees most of the other aspects that give adequate access to that functionality (see Section 6.3). This puts the developers of tools/techniques in a position where they have to demonstrate the scope and validity of a tool/technique in terms of scientific proof, and at the same time have to substantiate its worthiness for industrial practice. Consequently, the main question then focuses on who can build a business case out of such a combination in terms of elaborating, implementing, introducing, marketing, supporting and maintaining a tool/technique. In the future, the amalgamation of academic genericness and industrial applicability will have to become the main driver for effective and successful development of tools/techniques.

11.1. Tools/techniques as information processing means

From a rather abstract viewpoint, design work preponderantly consists of the search for and storage, retrieval, transformation, transportation, representation and interpretation of information [154]. At the same time, collaboration, particularly in design environments, has become an imperative for innovation. However, the 'knowledge explosion' and abundant connectivity may hamper rapid innovation and may lead to communication overflow [67].

Based on this reasoning, tools/techniques in product design are essentially information processing means. After all, all tools/techniques contribute to the timely, effective and efficient availability of the appropriate and required information. In that sense, they pave the way for designers, allowing them to spend less time on basic knowledge work and focus on what they do best: find creative solutions for the more challenging problems [53].

This, however, permeates the employment of tools/techniques with the same challenges faced by information management approaches. This firstly encompasses 'traditional' management problems related to e.g. security [19,224], intellectual property [97], risk [25] and training [44]. Secondly, often under-prioritised by designers, the sheer quality of the information may affect the usefulness of the tools/techniques. This addresses the fact that generally no tool/technique can produce high-quality output from inferior input. However, more important is the observation that designers often (have to) depend on the reliability of the information they use in their tools/techniques. Uncertainty and ambiguity are often disregarded, possibly because information management systems tend to have a rather binary approach to certainty, and many tools/techniques presuppose the existence of a fully defined set of information (e.g. a CAD model).

From a broader perspective, problems may also relate to the workflow related to tools/techniques in the hands of a design team. As this workflow is usually process-oriented, a direct link between the objective goals and – possibly – related processes and activities must be made almost instinctively and unconditionally. As a result, the relationships between production type, product type, environment and project management are needlessly aggravated. As it is impossible to foresee all potentially required processes and interactions, a compromise between being generic and being meticulous has to be found. This often leads to precedence relations and iterations that are misapplied to construct a form of ostensible hierarchy; this directly contributes to rigidity in the conjoint application of tools/techniques.

12. Tools & techniques: future developments

As mentioned in Section 1, this publication does not aim at constructing exhaustive lists of tools/techniques. As such, this section will also not address individual tools/techniques and predict their future use, decay or success. Alternatively, this section aims to address a number of dimensions that will play important roles in the way designers will envisage, select and employ tools/techniques. The starting point in this is that a tool is only a tool insofar as it is used as such to achieve the purpose of an activity. Obviously, the same is true for a technique. Consequently, the focus is here on what can be obtained by tools/techniques, not on rather far-fetched predictions related to e.g. not yet existing algorithms or revolutionary hardware breakthroughs.

12.1. Towards real-time processing

Despite the last remark of the previous section, evolutionary innovations in both algorithms and hardware will definitely affect the way in which designers will use tools/techniques. For example, the 'time to execute' – being one of the pivotal elements in Fig. 10, will decrease significantly. This allows for quicker results, but also for different ways of employing tools. Because tools will generate results more quickly, their operation mode will become more contributive than reactive. With this, designers will more quickly gain an overview of the (possible) consequences of their decisions. This allows them to search for, and assess, more solutions variants, or to foresee path dependencies more quickly in the development life cycle. Obviously, this contributes both to design efficiency and to design effectivity. Design teams can more quickly determine if they 'do things right', but also if they 'do the right things'.

However, the information processing demands imposed on designers will increase accordingly. This implies that designers should be aware of the risk that the core of their work might shift (even more) from primary to managerial activities. In itself, such a shift will further increase the difficulties in maintaining an adequate overview of a design project. With this, the prospective relation between tools/techniques and underlying systems becomes more relevant.

12.2. Tailored tools/techniques

Whenever the management of (outcomes) of tools/techniques is at stake, two different approaches are common: integration and specialisation. In the integrative approach, tools/techniques are combined into sets that are more unequivocal, cover multiple aspects and have aligned interactions with the user – often connected to underlying systems like CAD, PLM etc. At the same time, however, such sets tend to increase in complexity, run the risk of becoming less flexible and nimble, and usually have a steeper or longer learning curve.

The required flexibility, configurability and customisation in design projects (see Section 3) cause an inclination towards the specialisation approach, in which tools/techniques become smaller entities in the designer's 'toolbox'. With this, the use of tools/techniques can be tailored much more effectively to the design project at hand, without involving complex preparation and implementation trajectories. In practice this will mean that tools/techniques, but mainly the interfaces between them, will be more standardised, rendering a more modular approach feasible. This will allow for more lean and agile application of the tools/techniques. On the one hand, this allows for a closer fit between the set of tools/techniques and the design trajectory, whereas on the other hand requirements concerning training and expertise decrease. Given the reasoning in the above, this might simultaneously increase the burden of 'tool management' in design projects, but as the 'ease-of-use' of tools/techniques can improve, this is a relatively small risk. Precondition for this is that designers approve of the adage 'less system, more tool'. As a matter of fact, they most certainly will, as it allows them to focus more on the primary and creative activities in their work.

12.3. Information based rather than process based

Where tools/techniques become more tailored entities in the designer's toolbox and these tools/techniques generate more information quicker, it will be increasingly difficult to manage the design workflow from a process point of view. Defining that workflow by means of a series of interrelated and dependent process steps is nearly impossible, mainly because the interrelations only take shape during that same workflow. Given the basic assumptions in e.g. 'what-if' design [154], it is clear that a process-based approach will increasingly stifle the overall process. Moreover, with design teams increasingly working from different locations and time zones, collaborative work becomes the standard rather than the exception. As such, this calls for different tools/techniques [27,50]. Additionally, the boundaries of the design teams themselves become less clear, for example because of the many open innovation [39] initiatives. With this, the actors in a design project are less identifiable, rendering a process based management approach rather pointless.

Alternatively, the information content itself – mainly being the evolving product definition – can become the initiator and carrier of the activities of the designers and the design team. With this, the use of tools/techniques can be depicted in terms of the information they need as input and render as output, thus fluently amalgamating with the description of design activities as mentioned in Section 6.3. This merge contributes to a more lean and agile employment of tools/techniques. Consequently, tools/techniques can become generic facilitators of advancement, as well as being sheer problem solvers.

12.4. Networked tools

Design, to an increasing extent, becomes a 'democratic' process: many stakeholders actively participate in the design process itself, ranging from mass-customisation [72,178], co-creation [104,244] to exchanging 3D models for rapid manufacturing or even 'science fiction prototyping' [20]. Users, engineers and entrepreneurs have many cheap or free possibilities at their disposal to generate or adapt geometry. Inherently, tools/techniques in the design environment have to cope more with network structures than with the traditional design cycles. This involves more (types of) users, but also different ways of sharing information. Tools/techniques, more and more, will become information portals, where users aim to 'collect' information while not having the full expertise to influence the way in which that information is effected or presented, nor be able to assess the quality of the information obtained. Here, Virtual Reality (VR) and Augmented Reality (AR) might be instrumental [183], but only if the simulation itself does not produce a false sense of security.

It is not expected that professional design tools/techniques will become 'public' cloud services before long; however, in the end the democratisation of design will develop, significantly changing the role and behaviour of design tools/techniques. This will certainly be influenced by e.g. the level of expertise, training, cost and implementation time of the foreseen users.

12.5. Feasible can be good enough

As the sheer amount of information in design trajectories will significantly increase, the role of information in design projects will change. This not only calls for different management approaches, it also offers noteworthy opportunities. Phenomena like 'big data' [133], 'internet of things' [136,239] and 'data mining' [155] provide designers with an overwhelming realm of interpretable data. To transform this data into meaningful information, the traditional approach of deterministically scrutinising the data is no longer an option. However, in appreciating the fact that the magnitude of the information content can render the quality/reliability/certainty of individual specific information entities less relevant, tools/techniques can exchange 'scrutinising' with 'harvesting'. Given the increasing pressure on product development times, for many decisions, designers will rather have an adequate solution quickly, than a perfect solution too late. For many product developers, accepting the fact that not all information can profoundly be taken into account will be a paradigm shift. However, once that shift is made, also the role of uncertainty and ambiguity will change. Consequently, where possible, tools/techniques can be developed in such a way that they can inherently deal with incomplete, imprecise, uncertain and even lacking information to aid in decision-making. Where required, a further quest for information may be initiated by the tool/technique, or an indication of the probable validity of an outcome (and a sensitivity analysis thereof) can be provided to the design team.

12.6. Routine activities

To an increasing extent, tools/techniques will perform much work, without the designer even knowing about it; they will not focus on helping the designer to generate information that is required for a decision, but rather focus on the decision itself, by routinely collecting, generating and structuring the required information. In other words, tools/techniques will become instrumental in separating information harvesting from interpretation of information.

Designers are at their (creative) best, if they can focus on one task. For years, this has accordingly been the basic starting point of the development of tools. Therefore, designers too often have to 'ask' the tool to do something. That trigger, however, will move more to the overall workflow. If the information need is known, the tools can autonomously perform simulations in parallel that will probably be required or helpful further on. This may cause tools to create and assess results that will not subsequently be used; at the same time, this significantly can increase the efficiency of the designer. This is especially true if tools/techniques can autonomously identify obstacles in the design phases to come and can propose ways to deal with such obstacles. In this, the employment of tools shifts from a mere operational level to more strategic efforts; adjacent techniques need to be attuned to this.

Examples of the envisaged employment of tools/techniques are computational design synthesis tools [29,125]. Such tools focus on automated and semi-automated methods for a range of tasks focusing initially around synthesis, design generation, search and optimisation.

12.7. Towards the fuzzy front-end

Amongst the abundance of existing design tools, relatively few offer support to the conceptual design phases [10]. Yet, companies do acknowledge that conceptual design determines at least 70% of the product costs and affects the total course of the design process. A likely reason for this uneven spread is that design information in the early stages incorporates many uncertainties. In many design contexts, this contrasts with the inevitable demand of software-based design tools to capture design information in a limited set of explicit variables. On one hand, this calls for tools that are less deterministic in nature and can better deal with indistinctnesses. Especially the need to project consequences of early design decisions on the further course of the project (e.g. by what-if analyses [154]) leads to the expectation that many tools/techniques will move towards the fuzzy front-end (e.g. [84,208]), or that dedicated tools/techniques will be developed. Such tools will have to rely on a new 'language' that can relate the indefinitenesses and relative vagueness of the fuzzy front-end to the specifics of the design environment.

In this respect, requirements engineering will become an important asset for many tools/techniques, as it will facilitate the linkage between early stages of design to detailed design in a continuous process [40]. Based on concepts like RFBS (Requirement-Function-Behaviour-Structure) [41], semantics can aid in converting functions into the inception of (generic or abstract) structures. With this, the behaviour of a system can be predicted/derived and simulated, enabling an evaluation of the structure of the proposed system [42].

12.8. Industrial acceptance

As mentioned in Section 9, the relationship between academia and industry concerning the development of tools/techniques is not flawless. For the future, this implies that academia needs to focus on more than just the functionality of the tool/techniques, thus also developing approaches for e.g. implementation and training. At the same time, industry is developing a demeanour that allows them to express more profoundly what types of tools/techniques would improve their development cycles. Therefore, it is likely that industry and academia increasingly will be able to collaboratively work on the development of purposeful tools/techniques. Here, a balance between 'theory push' and 'technology pull' has to be found. In this balance, two other stakeholders play a significant role: suppliers/vendors of tools/techniques and IT-departments. The suppliers will more and more act as a broker, by simultaneously arranging for development resources and by facilitating profitable dissemination of the resulting tools/techniques. Additionally, such suppliers can fulfil an important role in the management of tool/technique portfolios in companies. As any IT department – by definition – influences, facilitates and curtails the employability of individual tools, toolboxes as well as the entire environment, the underlying infrastructure becomes relevant in tool usage. This is all the more true in appreciating the overwhelming increase in inter-organisational collaborative employment of tools and e.g. cloud-based services. With this, future developments of tools/techniques should thoroughly consider infrastructure and/or platforms that enable their employment. It goes without saying that industry may also enforce developments in the IT-sector that are geared towards a disengagement of the influence IT-departments have on the primary processes of designers and engineers.

12.9. Lacunas

With the changing role of tools/techniques in the design process, the composition of the designer's toolbox is also likely to change. Some tools/techniques become obsolete or less relevant; at the same time opportunities or demands for complements to the toolbox become apparent. Without running the risk of trying to define the 'optimal' toolbox or shortlisting the most promising additions to it, there are a number of clear focal areas where new or improved tools/techniques can most definitely be useful and would decisively facilitate design processes. Although many specific and detailed application areas could be identified, the main focal points are more related to the interface between individual design activities and the overall workflow of (interrelated) design projects.

In mentioning just a few dimensions in the design space that could benefit from reinforcements by means of more effective and efficient tools/techniques, decision-making and design rationale stand out. Given the increasing complexity of design projects and the interrelations between adjacent or subsequent projects, designers require better access to adequate and reliable information on the current project, but also to purposeful information on other projects. The latter not only entails best practices, but also information related to e.g. portfolio management and design/brand management. By far, not all of such information can be captured in formal structures; therefore, tools that can identify meaningful and related information in unstructured information carriers (like e-mails, social media or documents) will significantly contribute to the efficiency of design processes [53,246], while simultaneously avoiding lapsing into the old mistakes.

12.10. Embedding in environments

Focus increasingly shifts from individual tools/techniques to the toolbox that is available to the designer. Even more, the environment that yields the application area for that toolbox has an ever-increasing influence on the employment of tools/techniques. So-called Synthetic Environments (SE) can be used to bring together all influences on product development cycles, while achieving synthesis between tools/techniques, information, resources and control mechanisms to reach an adequate solution (product). Here, tools/techniques become an inherent part of the virtual meeting space. Generally speaking, a Synthetic Environment can be described as any deliberately constructed artificial environment that gives more insight into the real and natural environment; allowing an operator to navigate or interact as if in the real world. As a Synthetic Environment simulates a real world situation, its construction is usually based on virtual and augmented reality technologies [171]. The virtual reality (actually being a combination of 'virtual' and 'real' reality) that is used in SE's allows for the engendering of new objects, spaces and interactions. Advances in VR hardware and software have made much technology affordable to ordinary users. However, only 'clever' applications of the technology, with adequate attention for working methods, can convert the technology into purposeful tools/techniques.

It is obvious that the development of a Synthetic Environment also requires extensive preparation before its use can actually provide significant results in product development cycles. This preparation often is a consultation process between the client (e.g. an SME conducting design processes) and the host of the facility that realises the Synthetic Environment. Although manifestations and established advantages of Synthetic Environments are case specific (they depend on the strengths and weaknesses encountered in a company's development process), Synthetic Environments do have generic characteristics. With the underlying tools/techniques, they allow for [54]:

- realistic experience of virtual interactions, ensuring validity of decisions in the real world.
- simulated effects in a familiar context to stimulate stakeholders to develop a realistic mental image of a future product.
- congruent mental images of the future of a product or situation, facilitating negotiations about the consequences of their characteristics.

Typically, the environments in which tools/techniques are employed allow for, and rely on, interactions with many stakeholders. This brings such an environment closer to the everyday design reality, but at the same time imposes more constraints on the development of tools/techniques that drive the activities in such an environment.

In the European context, e.g. the Visionair project ('VISION Advanced Infrastructure for Research') [186] aims to gain experience with the interaction between environments, tools/techniques and stakeholder. By integrating existing facilities (e.g. of the 25 member laboratories), Visionair is aimed at creating a research infrastructure that will be open to research communities across Europe and around the world for conducting state-of-the-art research. The project aims to achieve this by permitting European researchers access to both physical facilities and virtual services suitable for their own research project by means of so-called TNA's (Trans-National access). In such TNA's the employment of tools/techniques in the context of the appropriate environment is paramount to the success of the project. Consequently, the Visionair project is a valuable driver in setting the standard for future tools/techniques.

13. Concluding remarks

Over the centuries, society has always been influenced by acts of design. With the increasing complexity of society and of the design activities themselves, designers have constantly developed tools/techniques to aid them in their work. At the same time, designers have aimed to diminish the complexities of their projects by purposefully reducing the number of influencing variables. Gradually, this has become an implicit way to maintain overview over design cycles. However, with the swiftly widening horizon of the average design project, such an approach is not sufficient to deal with e.g. the indefinitenesses and interdependencies in the project, different yet linked projects and all related stakeholders.

To decisively hold sway over the design environment, designers need to have access to a broad portfolio of effective and efficient tools/techniques that bring flexibility, agility and nimbleness. Whereas this obviously is a rather idealised picture, designers should never be hampered in their primary processes by the tools/techniques they are forced to use. At the same time, a designer must understand that some additional efforts in the current project may bring significant advantages to related or subsequent projects.

As an amalgamation of arts, crafts and science, design has always been (and will always be) a trade that involves subjective interpretation. With the increase of e.g. complexity and time pressures, it is clear that product design, to an increasing extent, becomes a non-deterministic process. More importantly, it stresses indeterministic characteristics to allow product designers to fully exploit their craftsmanship in establishing innovative concepts in large solution spaces, while simultaneously employing computer power to address routine tasks. In this, tools/techniques are indispensable assets that can pave the way for designers to develop products that not only excellently meet the requirements imposed by the market, but also fully allow designers to express their capacities. After all, only in the hands of competent craftsmen do the right tools become powerful.

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