

# Sketching in early conceptual phases of product design: guidelines and tools

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## ABSTRACT

*The early phases of product development play a significant role for the success of a product and the prevention of time and money consuming changes in late phases. This paper describes a new methodological approach for the generation of principle solutions in the form of sketches in early phases of product development. A guideline has been developed for a target-oriented and efficient progression from working principles to principle solutions. In particular, the linkage between physical effects and form parameters (geometry, materials etc.) has been investigated. A computer system including physical effects as features which can be used for the generation of digital principle sketches is described as a vision. Such a system offers the potential of facilitating routine work and supporting the engineer in defining solution concepts at early stages of product design.*

*Categories: Inferring shape from sketches, sketching diagrams.*

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## 1. Introduction

In early phases of design, concepts are created by defining functions to be realized, searching for adequate working principles and deriving principle solutions. In this phase sketching plays an important role since the level of information is still relatively low, the created product representations are fuzzy and not as exact as the CAD models which are created later in order to allow for manufacture of the product. A lot of expensive and time consuming changes in late phases of a project can be avoided by putting more effort into systematic, methodological proceeding during the early phases.

Within the scope of this paper a new approach to design in early phases of product development is introduced which focusses on a systematic derivation of principle solutions from working principles. The main idea is to link physical effects to corresponding form parameters.

A working principle reflects the physical effects needed for the fulfilment of a given function. A principle solution represents the concretization of the working principle within a working structure [PB\*96]. The principle solution comprises aspects like the overall shape, material or arrangement of product elements. Corresponding product representations are sketches, schematic drawings etc. as opposed to detailed CAD drawings which include all information needed for production (such as exact geometry, tolerances etc.). Common expressions used in literature for the same context are: form design, layout design, draft design or scheme design.

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Also, a vision of a sketching system is pictured which supports the processes in the form design phase.

## 2. Motivation of research

Before describing the new approach to the creation of principle solutions, the motivation of the research activity shall be explained. First, the importance of early phases of product development is stressed. This is followed by the consideration of how design methodology supports a systematic proceeding in this phase. Also, the reference to the topic of the workshop, sketching, is pointed out.

### 2.1 Importance of early stages of product development

Errors, unwise decisions and unsystematic proceeding in early stages of the product development process lead to expensive changes in late phases. This is a fact stated by many experts in industry. Important aspects with respect to this problem are:

- The information level in early phases is still low. Therefore the best solution to a problem is not obvious at once in most cases. Here, a thorough clarification and documentation of requirements, systems engineering and functional analysis can help cope with this fact.
- Often the first solution that comes in mind is chosen, worked out and elaborated. After spending a considerable amount of time and money, it becomes clear that there are flaws in the concept or important require-

ments have been neglected. Again, a careful clarification of the task is vital, as well as the explicit consideration of possible alternative solutions.

- Existing knowledge from previous projects is often not considered or used, the wheel is reinvented, so to speak. Helpful in this context are solution catalogues, (containing physical effects, machine elements etc.) for a targeted search for existing solutions. Graphical representations of the solutions contained within these catalogues (drawings, sketches, schematic figures) are an essential part of the information and helpful for a fast retrieval.
- The verbal description of problems or solutions entails communication problems, especially in processes where the information content is still low. There exist different points of view and a different vocabulary (provider vs. client, product designer vs. manufacturing engineer, technician vs. sales staff) By working with graphical representations, some of these problems can be dealt with more easily!

To avoid undesired effects such as the ones mentioned above special importance has to be placed on the early stages of product development. Here, requirements have to be clarified and solution concepts are created. In order to create high quality solutions while keeping the effort (time, cost) low, engineers should have methods, guidelines and tools at hand supporting them in this stage of the design process.

**2.2 Importance of sketching in early phases**

First concepts are rarely modeled in CAD systems since they imply the implementation of exact geometrical information. The images and ideas which arise in the mind of the engineer while working on a design task or problem are fuzzy and often undefined. Sketching plays an important role in this stage. Design is creating product representations: pencil sketches on paper, abstract schematic drawings, concrete illustrations of details etc. Two aspects of interest that have to be considered are:

- How are sketches created? This aspect refers to the tools and systems supporting the engineer in the creation of sketches.
- Why are sketches created? Which purpose serves the sketch? What is represented in the sketch?

Question number one, dealing with sketching systems, will be addressed in chapter 4.5. First of all, a closer look is taken on the second question. In order to give an answer, the underlying processes of design in early product development stages have to be considered.

**3. Methodological background**

In literature, there exist various procedural models indicating how design processes can be executed with efficiency and target orientation. In this chapter, the dimensions of the design process are looked at from a methodological point of view and the utility of sketching is considered.

**3.1 Processes and product representations in early phases of design**

In design methodology various procedural models have been devised for a systematic navigation through the design process. The four main phases according to Pahl and Beitz [PB\*96] are the clarification of the task, the conceptual design, the embodiment design and the detail design. When referring to the “early phases”, the focus shall be placed on the conceptual design stage within this context. A more detailed process model is given by VDI 2221 [PB\*96] (see figure 1).

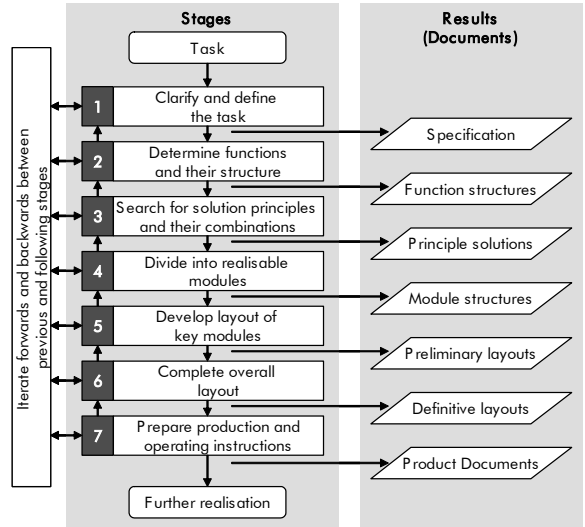


Figure 1: VDI 2221

The process starts with clarification and definition of the task and specification of requirements. Based upon these requirements, functions and their structures are defined and modeled. Then, working principles can be determined which are suitable for the realization of the defined functions. Principle solutions are created, the shape of the product, in particular the geometry, is elaborated in more and more detail until the product documentation is obtained, which allows further realization of the product (material acquisition, manufacture etc.).

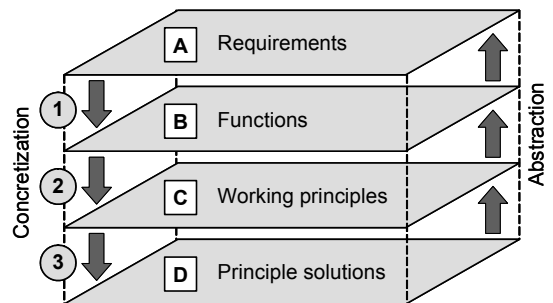


Figure 2: Simplified model containing different levels of product representation and process steps

In each step of the whole process product representations are created. Figure 2 shows a simplified model of the different levels of product representations. With each level from the top to the bottom, the product is more and more concretized.

In this context the focus shall be placed on the following process steps and corresponding product representations:

- from requirements to functions
- from functions to working principles
- from working principles to principle solutions

Of course the process does not stop here. The design has to be elaborated in detail with the help of CAD systems etc. Yet, these processes will not be addressed in this context.

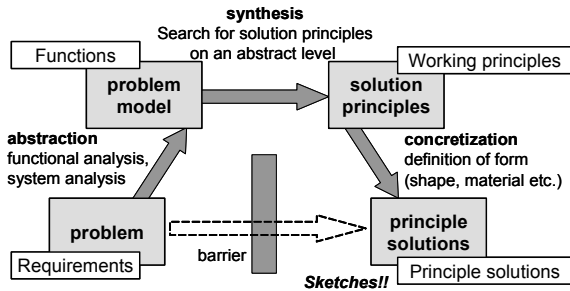


Figure 3: From problem to principle solution

Figure 3 illustrates the relations between the steps shown in figure 2 from a different perspective. A further explanation will be given in the next chapter.

### 3.2 Levels of concretization from problem to solution

A list of requirements represents the specification of a given problem indicating how the solution has to look like. The generation of a corresponding solution is not always a trivial case. Here, a systematic proceeding including a functional analysis and search for solution principles can help overcome this barrier.

#### 3.2.1 Functions

In order not to concentrate one’s focus on a particular solution and risking the neglect of a better one, the problem has to be analyzed on an abstract level. Function models offer considerable help to get a clear picture of the design task and to be free from fixation on existing solutions.

There exist various methods of function modeling, each focussing on certain aspects, and therefore each appropriate in certain situations. Functions can be structured in hierarchical function trees allowing to handle the complexity of a product by splitting up the overall function into sub-functions. If a product is undergoing many different operations while changing its status with each step, flow oriented function models are helpful. A relations oriented function model is able to point out not only the desired functions in a product but also the harmful functions.

The derivation of function models bases on the specification of requirements. It is essential to consider some basic rules while defining and formulating functions (such as a solution neutral specification). A function model can be extremely formalized. Ehrlenspiel [EHR\*03] for example only allows five different types of functions. But it does not necessarily have to be like that. A functional analysis

transforms the design problem into an abstract level allowing for a more systematic search for solutions, and by that enables the possible overcoming of barriers (like blockades of the mind, lack of creativity, solution fixations etc.).

#### 3.2.2 Working principles, physical effects

Once the functions a product has to fulfil are clear, it has to be investigated how they can be realized in principle. This is equivalent to a search for solutions on an abstract level. In most cases a function can be realized in many different ways, each of which has advantages and disadvantages. A solution might fulfil one requirement perfectly (e. g. performance, stability) but might stand in complete contradiction to another one (e. g. cost, weight).

The working principle can be described by the means of technical (physical, biological etc.) effects or as rather abstract principles such as described by Altshuller [ALT\*96]. Making use of Altshuller principles is also a method in order to resolve contradictions. This paper focusses on physical working principles.

Catalogues of physical effects can be consulted when searching for appropriate working principles. They are traditionally found in the form of paper catalogues. However, the operability can be enhanced to a considerable degree in the form of digital databases. Figure 4 gives an example how physical effects can be represented.

Name	Illustration	Formula
lever	Einseitig 	$M = F \cdot r$ $v = \omega \cdot r$
wedge		$F_2 = F_1 \cdot \frac{s_1}{s_2}$ $F_2 = \tan \alpha \cdot F_1$

Figure 4: Effect catalogue (excerpt)

#### 3.2.3 Principle solutions, form design

Promising working principles are given form in the next step. The solution has to be concretized. Here, sketching plays an important role. For the elaboration of a working principle there is an enormous number of design decisions to be made considering overall shape, detailed geometry, materials etc. Various aspects have to be taken into consideration that have an influence on the design such as ergonomics, manufacturing procedures, assembly etc.

Tools for this purpose are checklists with form parameters. An excerpt of such a checklist is displayed in figure 5 and figure 6. They can be worked through systematically in order not to forget important aspects in the conceptual and embodiment phase. They are an invaluable help in the variation of the design in order to improve flaws or weak spots and therefore optimize the design.

Categorie	Nr	Form design parameter
Area and volume body	01	Shape
	02	Position
	03	Number
	04	Size, extent
Relations of Area and volume body	05	Type of bond, linkage
	06	Type of contact
	07	Type of coupling
	08	Structure of bond, linkage
	09	Order, sequence
	10	Compactness of structure
Material properties	11	Type of material

Figure 5: Checklist form design parameters (excerpt)

Mobility	Rigid	Jointed	Elastic
Detachability	Detachable		Non-detachable
Type of bond (Type of fit)	Material fit (e. g. adhesive bond)	Force fit (e. g. friction bond)	Form fit

Figure 6: Detail checklist type of bond (excerpt)

On each level of concretization (functions, working principles, principle solutions) there exist various methods and tools for the generation and variation of corresponding product representations. Examples such as effect catalogues and checklists have been presented in this chapter. A new approach for the progression from abstract levels to more concrete ones is described in the following.

#### 4. Generation of principle solutions from functions and working principles: examples, guidelines, tools

Methods and tools to support the design process can help automate former manual operations, facilitate routine tasks or allow for a targeted and efficient navigation through the process. In order to illustrate the presented ideas more clearly they will be demonstrated on an exemplary product, a nutcracker

##### 4.1 Exemplary product: nutcracker

Consider the task of designing an innovative nutcracker. There already exists an abundant number of alternative product solutions. Three types of nutcrackers available on the market are shown in figure 7. Each of these nutcrackers works in a different kind of way.

However, many of these designs still contain flaws or potential for optimization. Requirements to consider are for example: compact format, no damaging of the kernel, low cost, simple working principle, portability etc.

In the three shown examples the kernel might be damaged while trying to open the shell. Also, there is no containment for kernel and shell. Once the nut is broken into parts, these might be distributed all over the place.

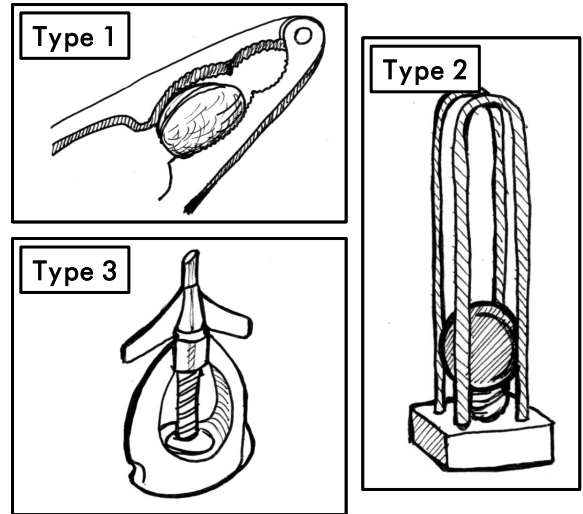


Figure 7: Nutcracker types

The first steps of the design task are the clarification of the requirements and a functional analysis, which will not be described within the scope of the paper. The two functions that will be looked at more closely are “apply splitting force on the nutshell” and “separate nutshell from kernel (after splitting)”.

#### 4.2 From functions to working principles

The step of deriving working principles from functions can be formalized and therefore automated to a certain degree. A function can be described as an operation turning physical input parameters into physical output parameters. Once input and output are defined, corresponding physical effects can be found by the help of a computer program. The automated generation of working principles does not guarantee the obtainment of the best solution. However, in situations where the lack of new ideas is predominant, an extremely formalized proceeding might help trigger the engineer’s imagination. There can be no complete automation of the design process, since it still needs human creativity and intuition in steps of analysis and synthesis.

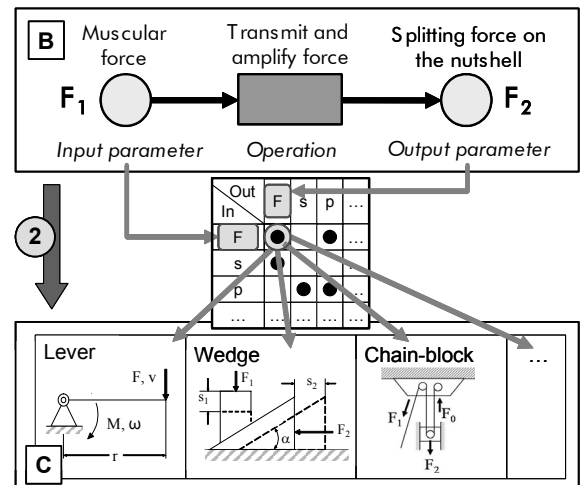


Figure 8: From functions to working principles

In the nutcracker example, the application of a splitting force can e. g. be realized by the amplification of a manual force. Input parameter is muscular force  $F_1$ , output parameter the (increased) splitting force on the nutshell  $F_2$ . Corresponding physical effects which can be chosen for the realization of this function are among others lever or wedge, such as realized in the nutcrackers of type 1 and type 3 (see figure 7). Figure 8 displays the function “transmit and amplify force” and corresponding effects as described in an effect catalogue.

### 4.3 From working principles to principle solutions

However, the effects from the catalogue only show the general physical principle, which still has to be applied to the nutcracker. This step represents the generation of a form solution and therefore a further concretization. Figure 9 shows the effects lever and wedge and their application on the nutcracker. Up to now, this step is not yet optimally supported by methodology or tools. There remain a lot of questions to be asked while executing this step. A more systematical proceeding can be enhanced with the approach described within this paper.

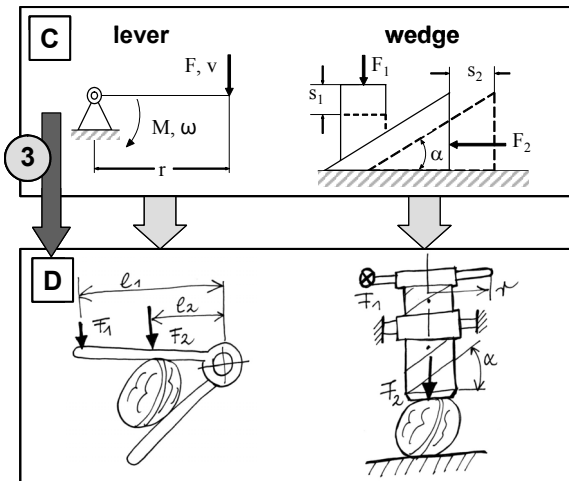


Figure 9: From working principles to principle solutions

The application of a physical effect to a given problem leads to a principle solution, which can be represented in sketch. These drawings show how the function of applying a splitting force to the nutshell can be realized in principle. A multitude of other solutions is possible, not only including mechanical, but also electronic, electromagnetic, pneumatic, hydraulic, thermal etc. effects.

Physical effects can be described by equations containing the relations between parameters such as length, mass, forces, temperature etc. The equations base on equilibrium conditions such as conservation of energy etc. In many cases geometrical parameters such as length, angle, area, volume etc. are involved. The choice of physical effect brings about a number of design decisions to be made in the following steps in order to concretize the solution. The step of progressing from working principles to principle solutions typically involves the creation of sketches. Physical effects are usually also represented by symbols or schematic illustrations such as shown in figure 9. To apply the

effect on a given problem, parameters such as shape, size and the allocation of elements are defined. The amount of product information is increased.

### 4.4 Linking physical effects and form parameters: a guideline

If the lever solution is chosen, parameters that have to be defined are for example: number of lever arms, length of lever arm, diameter of bearing, type of bearing (sliding contact bearing, rolling contact bearing). If the wedge solution is chosen, following parameters have to be defined: wedge angle (thread pitch), diameter of the drive screw, length of drive screw etc.

The example shows that, depending on the physical effect, different form parameters are addressed. Thus, once the working principle is chosen, there are still a lot of decisions to be made. And depending on these decisions, concrete solutions might look completely different even though the working principle is the same. This aspect is demonstrated in figure 10, where four different nutcrackers are shown which all base on the lever principle.

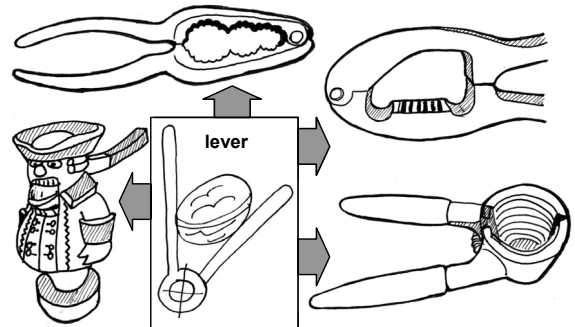


Figure 10: Same principle, different solutions

To facilitate the process of defining principle solutions basing on certain working principles a guideline has been devised. This guideline enables the engineer to keep the overview over the important parameters in this phase of the design and allow a more systematic proceeding.

- **Define functions to be realized.**
- **Choose appropriate physical effects as working principles for the given functions.** In many cases not a single effect is needed, but a chain of effects (in the nutcracker of type 3 the function “transmit and amplify force” is realized by combination of the effects lever and wedge).
- **Consider the major form parameters linked to the effect.** This does not yet mean the exact geometric specification, but the definition of the rough form dimensions. Linked to the effect are those form parameters which are of relevance for the corresponding effect. A checklist for these linkages between physical effects and corresponding form parameters has been worked out (see figure 11).
- **Sketch principle solutions.** The sketches represent the application of the effect(s) to the given problem.

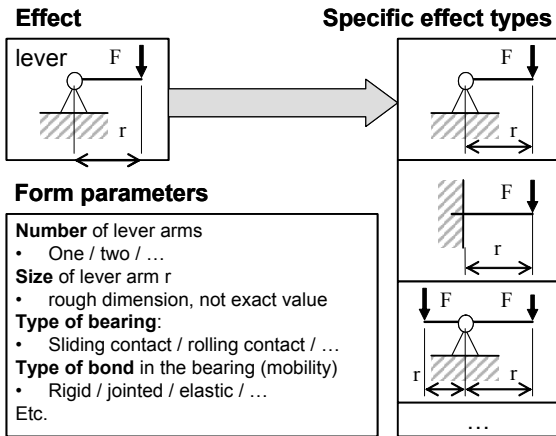


Figure 11: physical effects and linked form parameters

At the moment, a database is being implemented which allows for an automatic linkage between physical effects and form parameters.

#### 4.5 Vision: A sketching tool for principle solutions

The presented guideline is the basis for a digital sketching system where working principles (physical effects) can be included. The functionality of the system, which is still a vision, is conceived as follows (see figure 12):

- A menu bar shows categories of physical effects such as mechanics, electromagnetism, fluidics etc. (1).
- Each category contains physical effects depicted with symbols (2).
- Choosing an effect leads to a second menu where the effect has to be specified more exactly (3).
- A master of a principle working solution is created in the sketching area, where major parameters can be adjusted. The parameters do not necessarily have to be of geometrical type (e. g. material parameters as in the effect friction) (4).

Thus, physical effects can be handled analog to form features in CAD models such as drill holes, bolts and screws. The difference is that CAD features are on a more concrete level, while physical effects still contain many degrees of freedom.

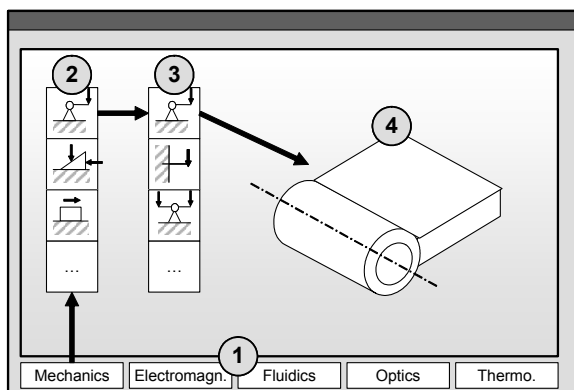


Figure 12: Tool for creating principle solutions (vision)

The tool would be useful for similar contexts as the system described by Kurtoglu and Stahovich [KS\*02], i. e. the treatment of mechanical, electrical etc. systems on a rather abstract level. Their system enables the recognition and interpretation of schematic sketches using geometrical as well as physical reasoning. The difference is, that the system focusses on sketch analysis rather than sketch creation, which is not supported (freehand sketches). Davis also describes systems developed at MIT enabling sketch interpretation [DAV\*02]. A combination of both functionalities (sketch creation and interpretation) might be promising.

#### 5. Summary and conclusions

This contribution describes a new way of methodological support for the generation of sketches in early phases of product development. The focus lies on a systematic derivation of principle solutions from working principles. A guideline has been developed for a target oriented and efficient proceeding supporting the designer with the decisions to be made along the solution concretization process. The functionality of a computer system basing on this guideline and including physical effects as features which can be inserted into a digital sketch is described. Further work includes the creation of a digital database with physical effects and form parameters, where the links are automatically generated, and the realization of the digital sketching tool where the depicted vision is implemented.

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