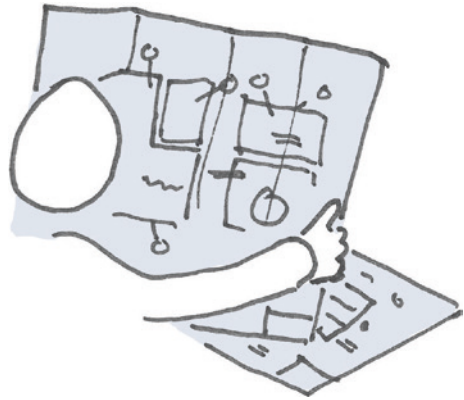


Chapter 8

Product Synthesis



The Product Synthesis activity, the third module in our Encapsulation Design Model, leads to the definition of how the product will be materialized, i.e. the composition of the design and its parts. The starting point is a selected concept, and the results are a full specification of the product. Parallel to this product synthesis also justifies the realization. The product related activities and the functions of product and activities need special care, with a focus on the search for proper solutions. Materialization means the definition of producible parts and their assembly, normally called embodiment design.

The core concept in this chapter is Domain Theory, which explains three interacting domains: activity, organ, and part. This theory serves as a backbone for explaining products' nature, the nature of their use, and the synthesis of these. This chapter explores how conceptualization is found in the details and how the concept synthesis actually leads into Product Synthesis activity.

8.1 Understanding Products' Nature and Synthesis

We use the sequence *Task/Concept/Design/Business/Use and Life* as the backbone for our model. The element **design** is the topic of this chapter. Following traditional terminology, however, we will talk about product and product synthesis, even though the real output is a specification of the product. Actual products only appear in the Product Development activity as a result of manufacture and sales,

see Chap. 9. Before we come to that, we must ask what is a design and what does Product Synthesis mean?

Product Synthesis is core to all types of design practice including, architectural design, food design, textile design, software design, and so on. Although we focus on engineering design, and mechanical products in particular, we use the general label Product Synthesis to underline the generic nature of the discussions in this chapter. In order to understand this we use Domain Theory (Andreasen 1980) as a foundation. This leads to a concept for ‘spelling’ the structure of the product and use activity. This allows the designer (and the reader) to decompose the degrees of freedom in which to search for solutions and compose the design. As such, we address the following topics in this chapter:

- Section 8.2 explores the **nature of Product Synthesis**.
- Section 8.3 examines how Product Synthesis merges knowledge about the **nature of the product** and about how people reason about a **product’s composition**.
- Sections 8.4–8.7 show how Domain Theory can be used to **‘spell’ the product and use activity** in three different **domains: activity, organ, and part**.
- Section 8.8 looks at how Product Synthesis is achieved by **progressing through these domains**.
- Section 8.9 examines how this gradual concretization and definition of the design can be captured in a **final product model** using Domain Theory.

8.2 The Nature of Product Synthesis

Product Synthesis is traditionally called engineering design (German: *Konstruieren*) but offers substantial insight for all areas of design application as noted above. Although many of the examples used here focus on products our treatment of Product Synthesis is such that translation into their other areas is feasible for the reader.

Historically, design was separated from production and sales resulting in almost all design starting with a goal statement (from management) and ending with a set of drawings (handed over to production). This is similar to our framing of Product Synthesis. However, as explained in our Encapsulation Design Model, Product Synthesis flows from Exploration and Concept Synthesis, and is part of the wider Product Development organization including marketing, sales, distribution, and service. Creating a concept can be seen as the core of new product development but Product Synthesis is the unavoidable craftsmanship needed to realize these conceptual dreams.

Product Synthesis is generally complex due to the numerous layers of sub-functions and the various interactions needing to be solved in the embodiment of the product. This leads to multiple part design and interface clarifications. Figure 8.1 illustrates the complexity of even a seemingly simple product, a bicycle. At the

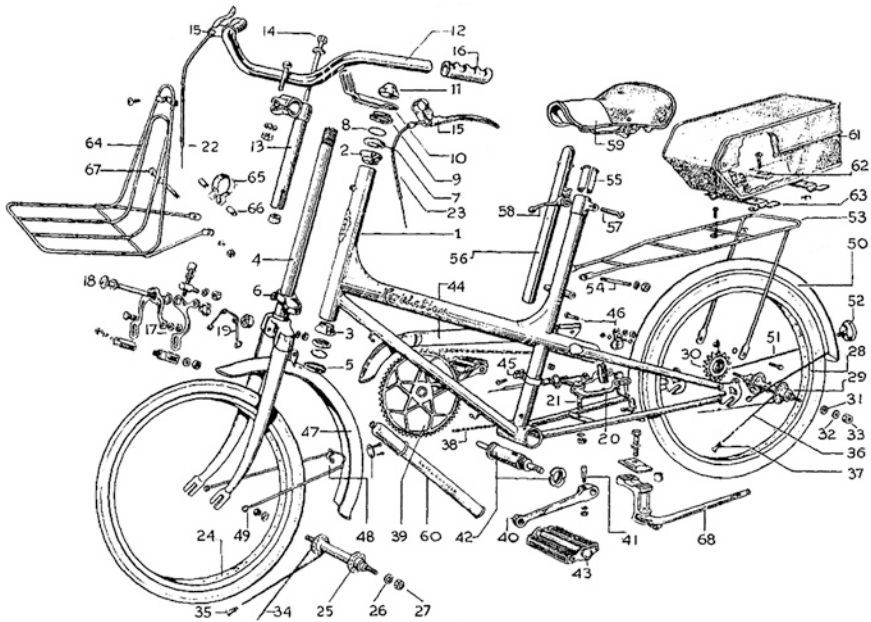


Fig. 8.1 The result of product synthesis is a complete determination of the design’s parts, here illustrated as an exploded view of a ‘Royal Enfield Revelation’ from the 1960s

end of Product Synthesis all these loose ends will be tied up with an unambiguous definition of the product’s composition, ready for production.

Even when using powerful CAD and product data management (PDM) tools the complexity of product synthesis results in a number of commonly experienced problems. First, **rework**, corrections, and changes often result from failures in cross-disciplinary communication or vague goal statements. These continuous changes result in significant difficulty in **managing change** propagation. For example incrementally new products aim for 10–20 % changes from the previous version, but often end up with 70 % or more. In this changing context remaining focused is a difficult proposition and results in the loss of the **designers’ intent**, i.e. the traceability of experiences and decisions. Here rework and incremental design are almost equivalent to start from scratch. Finally, these issues combine to reveal the **limitations of CAD**. In this context CAD’s geometry focus means it is of little help when reasoning about, e.g. functions, interactions, and activities. As such, product synthesis must be addressed through design tools.

Our focus can be illustrated using Cross (2008) model which highlights the layers of synthesis shown in Fig. 8.2. The internal layer defines eight stages in the design process, which are similar to concept synthesis. The core traits are goal formulation, search for solutions, and selection based on criteria. The outer layer is the symmetrical problem/solution model that concerns the composition of the solution. We can substitute ‘problem’ with ‘function’ in Cross’ model without

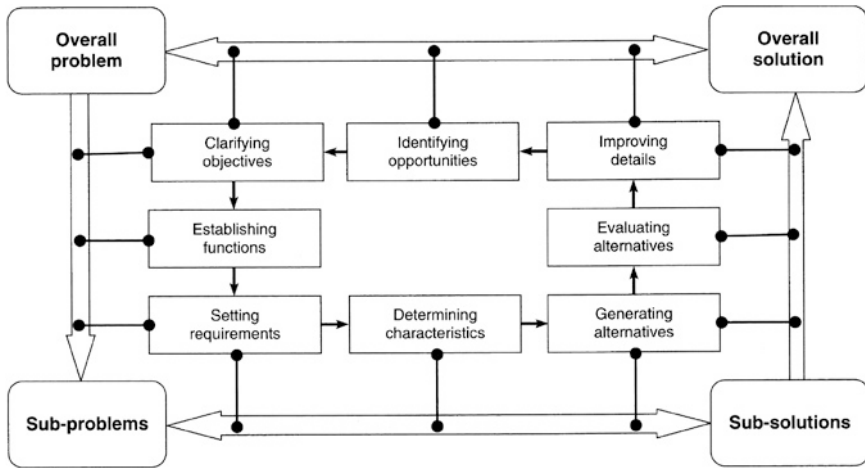


Fig. 8.2 The eight design process stages in the problem/solution model (Cross 2008)

changing its validity. As such, we focus on this outer layer, using sub-functions and their solutions as the key elements to be addressed when creating an integrated product.

Product synthesis is a design activity determined both from the nature of the artifact being designed and the designer's cognitive abilities. We focus on the artefact dimension in what we call 'spelling the product'.

8.3 Differences and Identities in Synthesis

Until now, we have discussed conceptualization generally, i.e. independent of discipline or the product's nature. However, here we narrow the scope to physical products, which are realized in industrial settings. This is a very broad field where each product area has its own synthesis theory, or at least practice. For example mechanical engineering works with machine elements and parts, electronics with circuits and components, food with recipes and ingredients, and so on. Each has their own language, way of reasoning, and rules.

The lack of a bridging, general synthesis theory is seen as a weakness of design methodology and is visible in the problems of multidisciplinary design. How far can we go in articulating a common ground? Which core aspects are common across products? There are commonalities related to the activities in which a product is used, the functions it realizes, and its material manifestation. This brings us to Domain Theory, which uses function as a bridging concept in order to help develop a shared understanding of product realization, relevant across product

areas. It corresponds with our view that good design support is obtained by creating a common articulation of the design entities, i.e. being able to create, model, and talk about the design in a cohesive way—what we call the ‘spelling’.

Our advice is to focus on approaches that primarily support the overview and progression of the design, and secondarily management and coordination. How specific designs in the shoe industry, in health care, in the food industry, etc. should be articulated requires special insight and is left to the reader. What we supply is the basic pattern of reasoning.

8.3.1 A General Foundation: Systems Theory

Before we explore Domain Theory, we first need to briefly discuss Systems Theory. This is an approach to the analysis and synthesis of complex artefacts, preferably composed of discrete, well-defined elements. Its development started in the 1950s to help deal with complex dynamic systems, such as strategic defence or airport control. Figure 8.3 illustrates the core elements of Systems Theory. Here a system is modelled as an object with respect to its composite **elements** and their **relations**. Together these form a **structure** with certain **behaviours**. The definition of elements and relations, and level of resolution is left up to the observer. The basic rules for system modelling are that elements should be of the same kind (e.g. not mixing devices and activities), and that relations should also be consistent (e.g. not mixing flow and time relations).

In daily language system has a broad meaning but in Systems Engineering (Blanchard and Fabrychy 1998; Ashby 1968; Hubka 1973) a system describes a model of a given object and its elements as outlined above. As such, Systems Theory forms a foundation that is used in many design theories (Pahl and Beitz 2007; Gero 1990; Suh 1990; Cross 2008) where a product’s components are seen as elements. However, one thing Systems Theory does not describe is how to proceed in synthesizing a design, instead it offers analytical insight. In order to

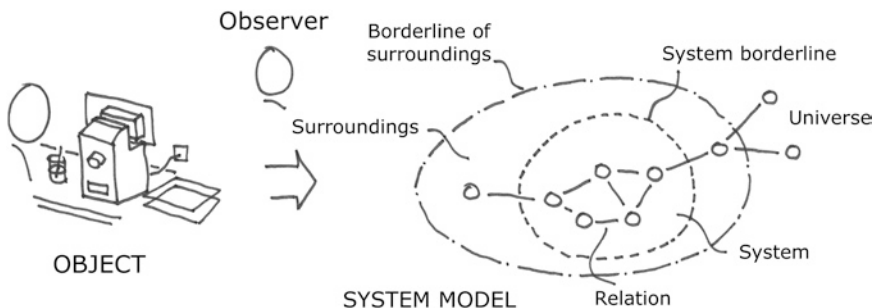


Fig. 8.3 The basic concepts of systems theory

address this synthesis aspect we look to Domain Theory, which utilizes Systems Theory in order to articulate its core concepts. We define a system as follows:

Definition: A **system** is a model of an object (a real or conceived product or activity) based on a certain viewpoint, which defines the elements of the system and their relations. A system carries **structure**, i.e. the elements and their relations (arrangement, architecture) and **behaviour**, i.e. the system's response to a stimulus depending on stimuli, structure, and state.

The game rules for system modelling are: elements should be of the same kind (not mixing, e.g. devices and activities), and the same with relations (not mixing, e.g. flow, 'kind of', and time relations). The power of Systems Engineering is that the basic features can be combined with technical theories and models (control theory, physics modelling, flow theories, etc.) to create more powerful models. Its strength is in analytical applications, not in synthesis. In the following, we show how Domain Theory utilizes Systems Engineering to articulate its basic concepts and add the nature of artefacts to Systems Theory.

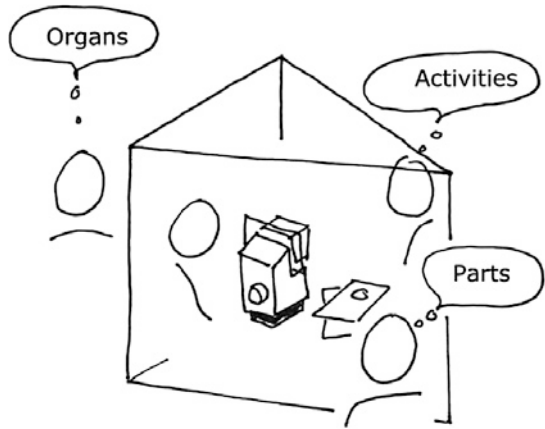
8.4 Domain Theory and the Three Ways of Spelling

Domain Theory is a development from an earlier theory originally formulated by Hubka in 1973 (Hubka and Eder 1988). In 1980 Andreasen transformed Hubka's theory into a "model based design theory"—Domain Theory. This provides a comprehensive set of concepts that allow the designer to model and synthesize products. These concepts are similar to those originally proposed by Hubka but have been developed to better support educational and practical application (Andreasen 1980). Domain Theory uses three domains (activities, organs, and parts) to cohesively articulate the nature of activities and products, providing a synthesis approach. It is a theory teaching us to "spell a product in different ways" using the different domains, illustrated in Fig. 8.4.

By departing from Systems Theory's general view where 'everything' can be seen as an element, Domain Theory prescribes three views: one focusing on the activity, and two focusing on the product (technical system). We propose a vocabulary of different 'languages' associated with each of these three domains. We illustrate each with an example of a drilling machine.

- The **activity domain** focuses on how the product is used (drilling machine: how it is used for drilling holes), including the product's lifecycle.
- The **organ domain** focuses on what the product is able to do, i.e. how the functional elements interact to create the effects necessary for the activity (drilling machine: motor, transmission, and clutch transmit force, momentum, and rotation to the drill).

Fig. 8.4 Domain theory's three perspectives



- The **part domain** focuses on the products' parts and their interfaces. This is realized in manufacturing and brought together in the assembly process (drilling machine: the housing of the drill carries the components and creates a hand grip).

How are these domains related? Basically, each is an independent explanation of the product: **how it is used, how it functions, and how it is built**. This is illustrated in Fig. 8.5 with respect to a classic Moka Pot. Here we can explain the pot via each domain: *activities*, e.g. to prepare the Moka Pot and put it on the stove;

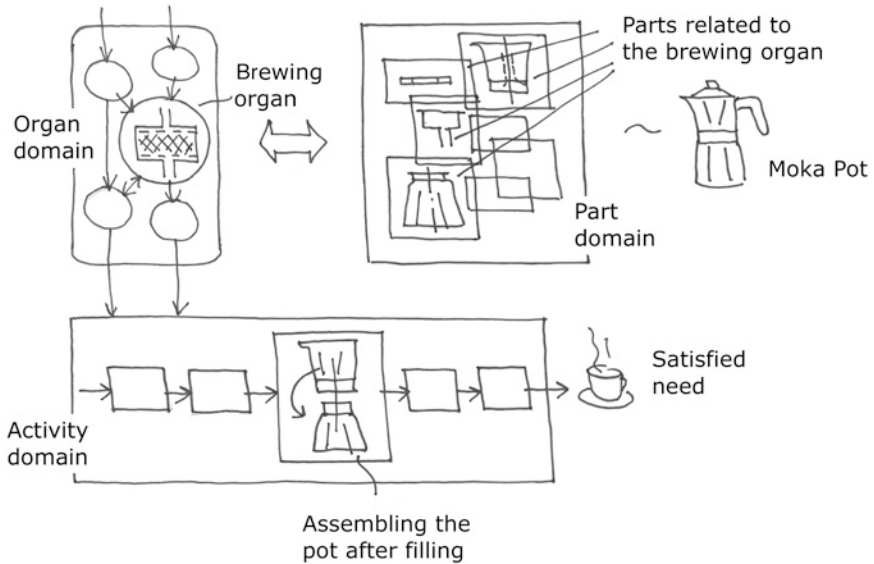


Fig. 8.5 Symbolic illustration of the relationships between domains

organs, e.g. the brewing organ, and *parts*, e.g. the threaded connector linking the boiling and serving pots. We can now consider the links between the domains. For example the organ structure (the product) should deliver the effects necessary for the activity, and the part structure should realize the organs as a viable product. These relationships underpin Domain Theory and its role in Product Synthesis.

In the following sections, we will examine each domain, their contribution to conceptualization, and their role in synthesis.

8.5 The Activity Domain: How the Product Is Used

The activity domain describes how the designer imagines or observes a product being used in practice. Our main interests are what the product can be used for and what the product can do. This close relationship between product and use activity is articulated in the definition:

Definition: Product is any kind of materialized and executable artefact, i.e. able to carry behaviour and properties in order to realize functions and be deployed in a **use activity**.

The link between product and use activity can be decomposed with respect to a number of operators. These were originally proposed by Hubka and Eder (1988) but have been adapted here for clarity. The four main operators are outlined here and illustrated in Fig. 8.6.

- **Products** are tools or machines and deliver effects in the form of material, energy, information or biological entities interacting with the operands (the subject of the operation).
- **Humans** that operator directly or indirectly through the product.
- **Methods** are the work patterns, knowledge, information, and data necessary to control the product or humans' action. These can be seen as a procedure that directs the activity.
- **Active surroundings** are the environmental influences (gravity, water, wind, etc.), as well as given systems, e.g. energy supply, waste removal, cooling air.

All activities are based on natural phenomenon, e.g. the cutting of paper with scissors or brewing beer based upon yeast culture. Utilization of natural phenomena is also found within the products themselves and is core to their operation, e.g. electromagnetism in a drilling machine's motor. In the following example, we explore how these elements are combined in a real product.

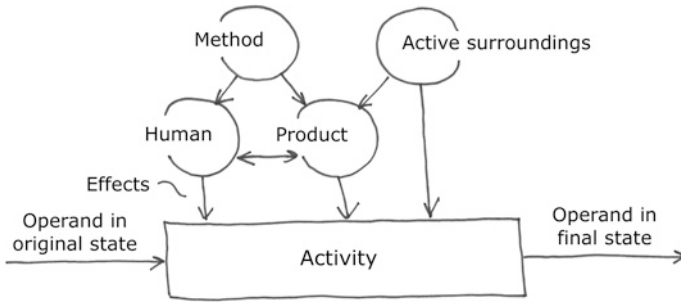


Fig. 8.6 The fundamental interaction between product and activity explained by operators and operands

Example:

A grill as a technical system. When a grill is used to prepare food the grill can be considered as a technical system where the operands are the food. The operator controls the process, as well as preparing the grill (positioning, lighting the charcoal) and closing it after use (disposal of ashes, cleaning, storing). The charcoal provides the energy input, while the grill transmits heat and supports the food. Further, environmental preconditions for grilling are available, oxygen, gravity, and air movement. Figure 8.7 shows a model of the activities related to preparing and finishing the overall grill activity including the food preparation.

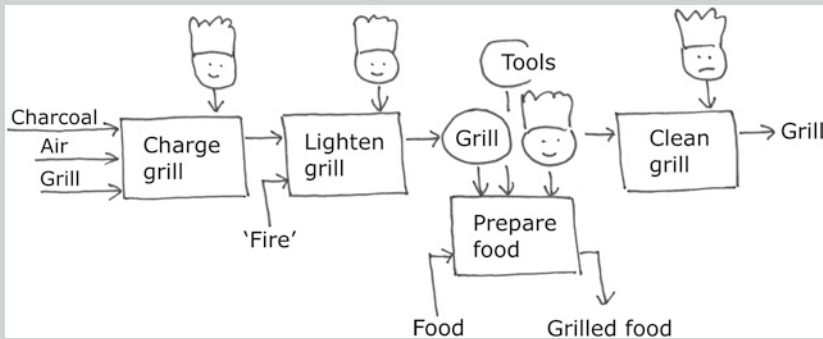


Fig. 8.7 Activity model of grilling. The operators ‘method’ and ‘active surroundings’ are not shown

The grill example highlights the two main patterns of activity. The first is the core **operation activity**, where the product is the operand and the food is grilled. The second is the **use activity** where the product, i.e. the grill itself, is the operand being influenced by the human and other products, e.g. cleaning devices. The use activity normally contains many single applications that together constitute the product's service period. As such, this can be formulated with respect to the lifecycle: The **product lifecycle** includes all activities related to the product from manufacture through to disposal. These are explained in Fig. 8.8, again using the Moka Pot example.

In an activity there are four different types of **operands** that are transformed: **material**, e.g. liquids or gases, **energy**, e.g. electricity or inertia, **information**, e.g. control data or speech, and **biological objects**, e.g. active bacteria or humans. Output from the activity is described by the operands in their final state, see Fig. 8.4, and constitute the outcome of the products use. For example a final state operand of the grill is grilled food, or brewed coffee in the Moka Pot. The value and utility of the product is connected to these outputs. The satisfaction of needs is established when the product is applied, not when it is sold.

The operation activity is related to a product's use. The product, together with the user, leads to the result of the operation activity, which (hopefully) satisfies the initially unsatisfied need.

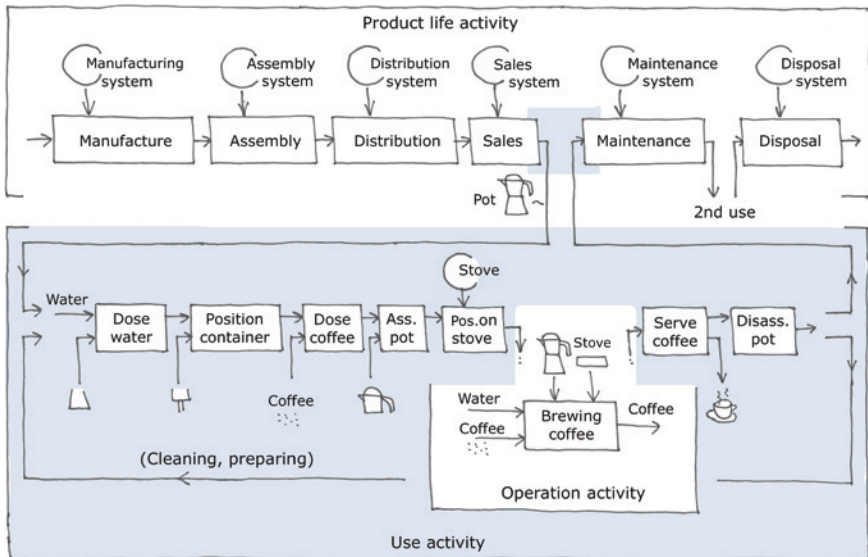


Fig. 8.8 A product lifecycle for a Moka Pot

8.5.1 The Activity System

The activities related to a product can be seen as a **system of activities**. The elements of this system are single activities and the relations are the operands. In the examples above we find simple linear, material-oriented systems. These are derived from a product’s **mode of action** based on its key principles. In the same way an activity’s underlying principles create its **mode of operation**. A drill’s mode of action is the transformation of electrical energy into rotation of the clutch; its mode of operation is drilling via the rotating bore, which creates the desired holes. Here, technology describes the physical way in which this is achieved.

There exist an enormous number of technologies like harvesting-, food-, tel-communication- and manufacturing-, all characterized by a great number of machines, products, and tools. A technology is the sum or interaction between a product, the activity, and its result. For example one role of riveting technology is the use of riveting machines to insert rivets when assembling metal plates in the aircraft industry. However, the designer may see the connecting rivets themselves as a technology. Figure 8.9 shows some simple examples of technologies described in our terminology.

8.5.2 Designing an Activity

Here we can look back on a classic question: which came first, the chicken or the egg or perhaps in our context, cycling or the bicycle? This leads us to the idea of dual synthesis, which in some situations is obvious: a can opener design starts with the activity of use. However, a chair designer rarely starts by asking, what is sitting? Fundamentally, when we aim to produce something that is a radically new way of satisfying a recognized need we must first understand what ultimately satisfies that need. In doing this we must answer the following questions:

- What shall be transformed into what final state? What is the operand and what should its final state be, e.g. opening a can.

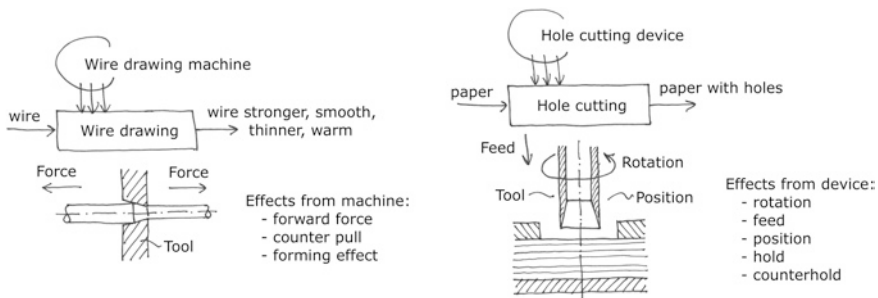


Fig. 8.9 The mode of operation for wire drawing and hole cutting activities

- What natural phenomenon, principle or mode of operation can be used to create this transformation? For example a traditional can opener uses a cutting knife that proceeds along the can's rim.
- What environmental conditions are necessary for the proposed mode of operation? For example an electrical power supply.

These raise the more philosophical question: can an activity be designed independently from the product? Typically, the relationship between a product and its associated activity is fundamental. For example the bicycle and cycling are innately linked, cycling alone is hard to imagine as an independent invention. As such, it typically requires more than one idea or design in order to invent a new product: one concerning its use activity and one concerning its functionality. For example the Segway builds on a novel use activity in its steering, coupled with a new application of existing technologies in order to provide its motor and stability functions.

A general approach to finding new solutions is to systematically modify the characteristics of known solutions, leading to the following heuristics:

New concepts related to activity may be found by varying how the technical activity is characterized:

- The mode of use or mode of life.
- The nature of the operand or alternative operands.
- The sequence of activities.
- The allocation of tasks between the user and the product.
- The type of effects from the operators.

New designs often build on known technologies, frequently with the existence of production technologies as a precondition (Arthur 2009). As such, one strategy when searching for new ideas is to focus on understanding the underlying phenomena and subsequently find means to solve, or bypass, inherent technical problems. For example consider the problem of generating continuous suction when vacuuming. The apparently inherent problem of the waste bag becoming clogged was bypassed by using bagless technology. An alternative strategy is to search for novel applications or use activities for existing or emerging technologies. For example laser cutters combine well-established technologies to give a new output. In either case ideas can be developed that idea require experiments to be clarified, and both strategies can yield concrete current solutions and more conceptual principals to be incorporated in totally new designs.

8.5.3 Models in the Activity Domain

The synthesis of product and use activity is often overlooked in the creation of new products simply because an underlying assumption is that the use shall automatically be derived from the way a product works. This not only results in the

potential poor performance of the design but also reduces the possibilities for identifying original ideas in the use dimension. As such, we recommend explicitly modelling the use activity as a support for the creative process, focusing on the following criteria:

- The temporal and/or physical **sequence of activities** leading to the transformation of the operands.
- The **state change** of the operand. In particular, what the input operands should be and what steps are required in their state changes.
- The **mode of use** or natural phenomenon to be utilized in the transformation and its arrangement in space and time.
- The **allocation** of tasks between the product(s) and the operator(s).

There is a rich palette of modelling types able to support the designer in this synthesis activity ranging from less formal sketches, computer animations or verbal presentation to more formal models, such as use cases and Function Analysis Diagrams. Here, pictures are easily understood, informal text is instructive, and formal models may be sharp but can be difficult to relate to reality. Together with spelling the activity these serve a key role in creating activity concepts.

8.5.4 Spelling an Activity

When creating a new concept there are several elements in the activity domain that demand clarification. This provides a core for the concept and can provide inspiration for its solution. The following heuristics provide guidance for using the activity domain in practice. These elements are all potential starting points for conceptualization. Considering these activity elements ensures that an idea can address what the product will actually do as well as its overall function.

The **human need** is satisfied by the output from the use activity. Therefore, the design and explicit articulation of the use activity are critically important.

When **new technologies** are needed to realize the use activity the search for, or design of, these new technologies can form the core conceptualization activity.

The **role allocation** between the product and the user must link to the use activity. As such, new concepts can be created through novel allocation.

When the use activity is expanded to include the whole **lifecycle** the designer must also conceptualize the lifecycle elements, e.g. service, upgrade, reuse, and disposal.

8.6 The Organ Domain: How the Product Functions

As illustrated in Fig. 8.5 two of the domains in Domain Theory are internal considerations related to the product's functional units—the organs and its physical elements—the parts. To clarify, the organ domain describes the functions in a product, while the part domain describes the parts and their assemblies. In order to identify organs a different type of reasoning and abstraction is required from what we might use to identify simple parts. Returning to the bicycle as a common frame of reference we can explore this reasoning further.

Example:

A bicycle's organs. Figure 8.10 shows the basic structure of a bicycle and below we outline one possible proposal for the bicycle's organs:

Rolling organ: This organ provides the ability to move with low resistance via the wheels and their interaction with the road.

Force take-up organ: This organ transfers the forces from the user through the pedal arrangement and the crankshaft to the transmission organ.

Transmission organ: This organ consists of two chain wheels, the chain, and the stiff connection between their bearings in the frame. The front chain wheel shares the crank bearing with the pedal arrangement, while the rear chain wheel shares the rear wheel bearing.

Drive organ: This organ transforms rotation energy to a force on the road, driving the bicycle forward. It consists of a driven wheel and output via the tire surface in contact with the road.



Fig. 8.10 Bicycle terminology, courtesy Daniel Barreneche

Steering organ: This organ directs the bicycle through the front wheel, head tube axis, and handles. Its output is a force on the road and a counterforce on the front wheel. A precondition is force take-up from the road and force transfer through the headset containing a bearing system.

Structural organ: This organ supports the user and transmits their weight through the frame and wheels to the earth. This also positions and supports all the other organs.

From this example we can draw some general points:

- Singular organs necessarily interact with other organs to achieve their functionality as well as contribute to the overall functionality.
- Entities can serve more than one organ, e.g. the rear wheel contributes to the rolling organ and the drive organ.
- Individual parts do not follow the organ composition. The individual parts shown in Fig. 8.10 do not offer a full explanation of the bicycle.

When identifying functions we ask: what are entities doing? And answer with action words, such as drive, force, transfer, etc. In contrast, during synthesis we start with a function and ask: what could do this? In this way we can use functional statements as a basis for finding solutions, i.e. organs. As such, we can define an organ as follows.

Definition: An **organ** is a system element of a product (when we see the product as a system from the function perspective). An organ is characterized by its function and mode of action, i.e. what it does and how it works.

In order to identify organs we must take a dynamic perspective on the product, examining what happens over time, i.e. what state transitions occur (see Chap. 12 for more). As organs are based on natural phenomena, the organ interacts with the surroundings when external effects (stimuli) act on it. Some of these effects can then be utilized as functions.

Organs are the functional building blocks of a product. They are the solutions that the designer constructs such that their interactions lead to the desired overall function. These interactions are normally chains of effects. The composition of organs is called an organ structure.

Definition: From a functional perspective a product is a **system of organs**. As such, a product's **organ structure** is defined by the organs (its elements) and their interaction (its relations).

Using this logic we can re-examine the bicycle example from earlier. Here, the interactions between the organs can be easily identified in the example: rotational force from the feet is transmitted through the transmission organ to the bicycle's drive organ and then to a force on the road, driving the bicycle forward. The organs' functionality depends on these interactions.

In order to realize these functions organs build on natural phenomena, such as physical, chemical or biological effects. Thus, the kernel of product synthesis is in the identification and arrangement of such phenomena (via the organs) into a whole that is able to realize the necessary functions.

Example:

A 'corkscrew's' mode of action. Wine bottle corks can be removed by penetrating the cork with a needle and pumping air into the bottle until the pressure is so high that the cork pops out. The product is similar to a small bicycle pump. Its main functions are to create air pressure and give access to the air space under the cork. These are realized by the pump and the hollow needle respectively. Another concept for a 'corkscrew' is to press a thin steel plate between the bottle's neck and the cork. This changes the friction and when the plate is pulled out the cork follows. The physical effects utilized in the two products are thus pressure increase and changing the coefficient of friction.

8.6.1 Models in the Organ Domain

In Fig. 8.2 we saw Cross' illustration of the problematic mapping from sub-functions to sub-systems, i.e. organs. Composition models in the organ domain thus describe both the **organs** and their **interactions**. There is again a range of approaches to modelling this system; however, they should typically aim to clarify the **mode of action**. Ultimately, considerations from the organ domain are linked to progress in the parts domain and it is thus typical for these to progress in parallel. Although organs are fundamental to product synthesis, they are much more difficult to immediately imagine in comparison to parts. In an effort to help mitigate this we will present a number of different organ models in order to help the reader get used to thinking in terms of organs.

One possibility is using **function language**. Here, instead of focusing on the organ as a concrete solution we focus on the organ's functions. Functions are the useful effect delivered by the organ. As such, we define the product via a system of function labels, e.g. create force, conduct current, create closure, and position needle. Figure 8.11 shows one such model, where a product's organ composition is articulated via functions.

Example:

Function labels. Bang and Olufsen sponsored project aimed to design a multi-store CD player (Hede Markussen 1990). Discs to be played are brought into the device (a), clamped (b), and transferred to the player (c). Alternatively, discs can be loaded without being immediately played. Here they continue from the clamping (c) into a circular store where the disc is secured (d). The functions related to these activities are described in the spatial arrangement illustrated in Fig. 8.11. Here, a, b, and c each represent an organ.

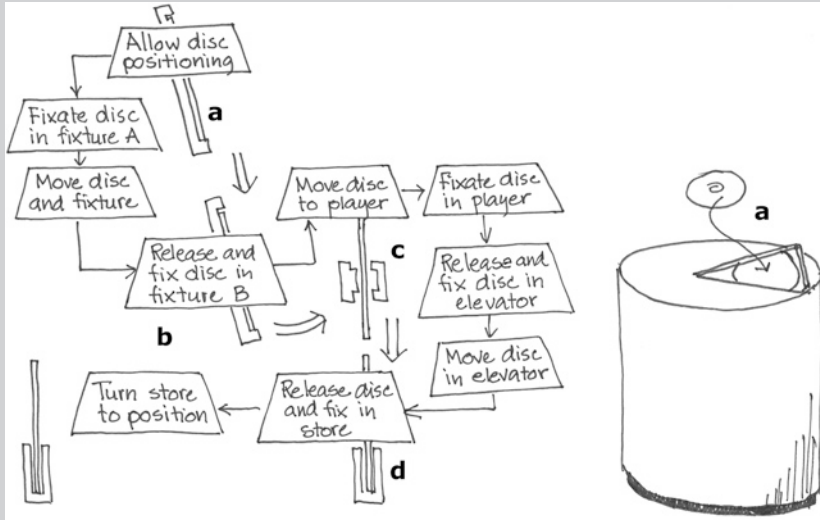


Fig. 8.11 An example visualization of a product’s organs using function labels

An organ’s **mode of action** (German: *Wirkungsweise*) can be articulated using simple symbols to describe a product diagrammatically. This technique is typically used for diagrams in, for example electronic or pneumatics circuits and train systems. Figure 8.12 describes the functions of a Tea maker in symbolic language.

Another way of modelling the organ domain is illustrated in Fig. 8.13. This shows the layout of an actuator with the parts and their relations. On the left is the technical layout drawing and on the right is the same assembly represented as a symbolic mechanism. This shows three arms that transmit force and move relative to each other about a central pivot. In this way the symbolic mechanism representation can be used to describe the organ (Courtesy Troels Petersen and Jens Peter Poulsen).

In electrical engineering there is a standard language for components (compositions of parts) that allows organ structures to be modelled at a generic level (circuit solutions) and at a quantitative level. In mechanical engineering it is more difficult to use similar standard representations because solutions are often superimposed over each other such that components serve multiple purposes, e.g. the frame in a bicycle.

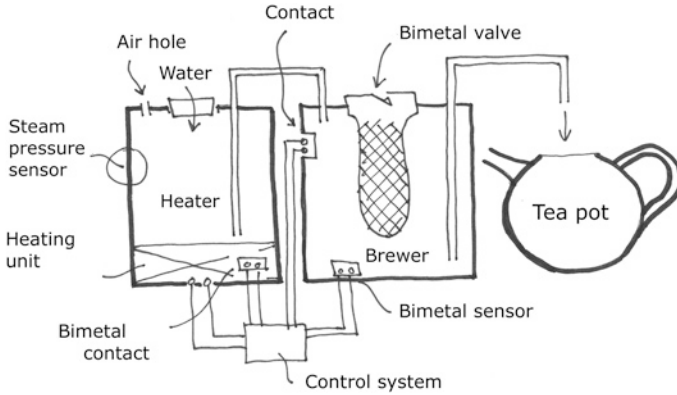


Fig. 8.12 Symbolic representation of the organs and their interaction in a tea maker

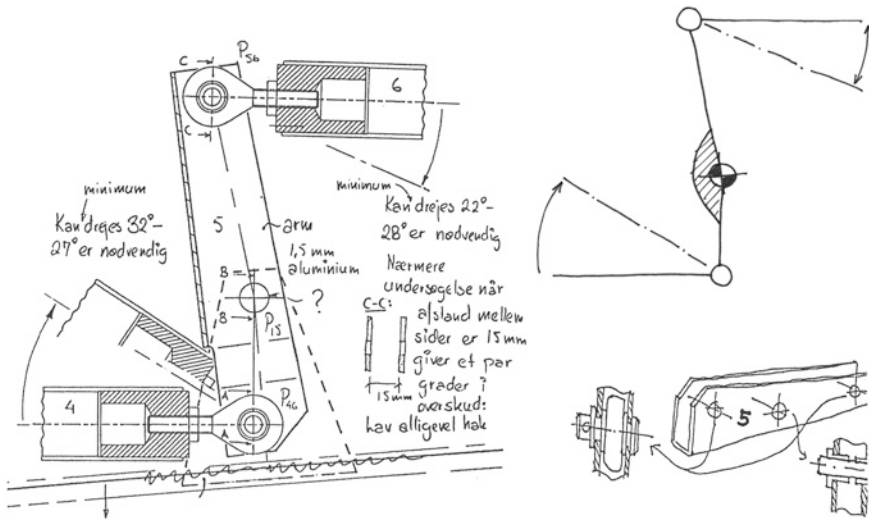


Fig. 8.13 Reading an organ structure from a part structure drawing

8.6.2 The Organ Domain as Concept Inspiration

Any technical idea actually describes organs by finding the mode of action based on natural phenomena. Therefore, many of the approaches mentioned in Chap. 7 (Concept Synthesis) can also be applied in organ synthesis. Organ thinking includes both of those organs hidden in the interior of a product and those that interact with the environment, e.g. interacting with the user or tool organs like a robot's gripper. When we articulate or 'spell' a product concept several organ heuristics should be considered.

- One starting point for synthesis is in the search for appropriate organs that **deliver** the **effects** demanded by the use activity.
- Articulating functions in a **solution neutral form** forces us to consider alternatives.
- **Articulating functions** focuses the search for solutions by providing abstractions that lead to organ classes, e.g. motor or operating organs.
- Organs should be **composed** with respect to the sub-tasks and sub-functions of the product (Fig. 8.2).

Ultimately, the model of the organ structure should provide sufficient detail that it can be handed to another designer who could reasonably be expected to complete the detailing with minimal further input. As such, organs need to be described in detail where their characteristics are specified with respect to the principle of the organ. Tjalve (1979) illustrates the transition to part structure in the example below, showing the qualitative and early quantitative considerations.

Example:

Tilting mirror. In an optical device, e.g. a periscope, a mechanism is needed such that an operator's input movement tilts a mirror in order to change the angle of the reflected light. Figure 8.14 shows alternative principles (a), a selected principle (b) and its variations (c), and the variant that leads to the illustrated part structure (d). The transmission mechanism is one single organ. The final picture shows how this is attached in the device, as well as its input lever.

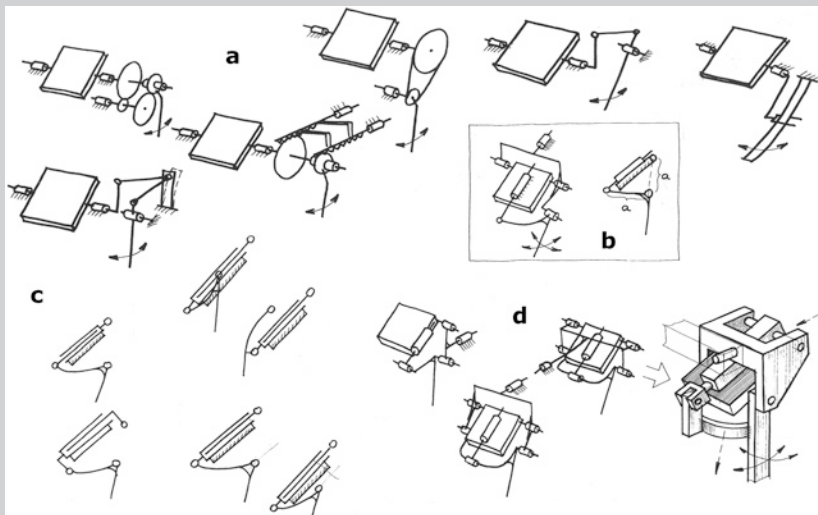


Fig. 8.14 Tilting mechanism's organ design and materialization illustrated by Tjalve (1979)

8.6.3 *Spelling the Organs*

One of the key reasons for the three domains of Domain Theory is to allow the designer to identify and utilize different design perspectives or degrees of freedom. The following heuristics articulate the degrees of freedom in the organ domain.

The organs define a product's functions and properties. Therefore, it is important to understand their physics and **mode of action**.

Understanding an organs **operating principle** allows for assessment of alternatives, as well as providing a foundation for materialization.

The organ structure describes how the effects necessary for the activity are achieved. However, do not aim at completeness; **move to the part domain** when concretization is needed.

Although some designers prefer to design based on part reasoning we recommend that at least a rough organ structure be described. This is because in the part structures' complexity the **function aspects of organs are easily lost**.

The organ domain provides a **common ground** between different disciplines. Using function reasoning allows actors from all disciplines to contribute to the product synthesis discussion.

We see reasoning about functions and organs as a necessary precondition for a deeper understanding of how a product functions and thus how to generate alternatives, to reuse or 'steal' solutions, and to empower their performance. In order to complete this understanding organs and their functions must be materialized as parts. The part domain, explored in the next section, addresses this materialization.

8.7 The Part Domain: How the Product Is Materialized

Many designers feel themselves most comfortable working in the part domain. Working with specific parts gives a tangible basis for reasoning resulting in sketches and concepts that focus on the part structure. The limitation of this approach is that the parts do not necessarily explain the functionality and interaction of the organs. In this sense the part orientated approach does not support the search for alternative solutions because it is always limited to a search for substitute parts rather than entirely new approaches or phenomena. In the mirror example above (Fig. 8.14) consideration of organs allows us to search for entirely new

ways to transmit the light, which could include video or other alternative means. In contrast considering only the parts might allow us to refine the current assembly e.g. replacing the mirror with a new material but does not allow us to re-examine the fundamental function of the mechanism. As such, the part and organ domains should be used in complement to each other throughout Product Synthesis.

As with organs, parts' behaviour is based on natural phenomena, e.g. stiffness or conductivity. In this way specific parts can help achieve the desired effects, e.g. piezoelectrical crystals can be used to create electric current. These characteristics link the parts to the organ domain. Here, the organ domain explains behaviour and functionality, while the part domain explains how this is 'built', i.e. the embodiment of the parts and their relationships in the assembly. This leads to the following definition of a part.

Definition: A **part** is a system element of a product (when we see the product from the embodiment perspective). A part is characterized by its physical properties, e.g. form, material, dimensions, and surface qualities.

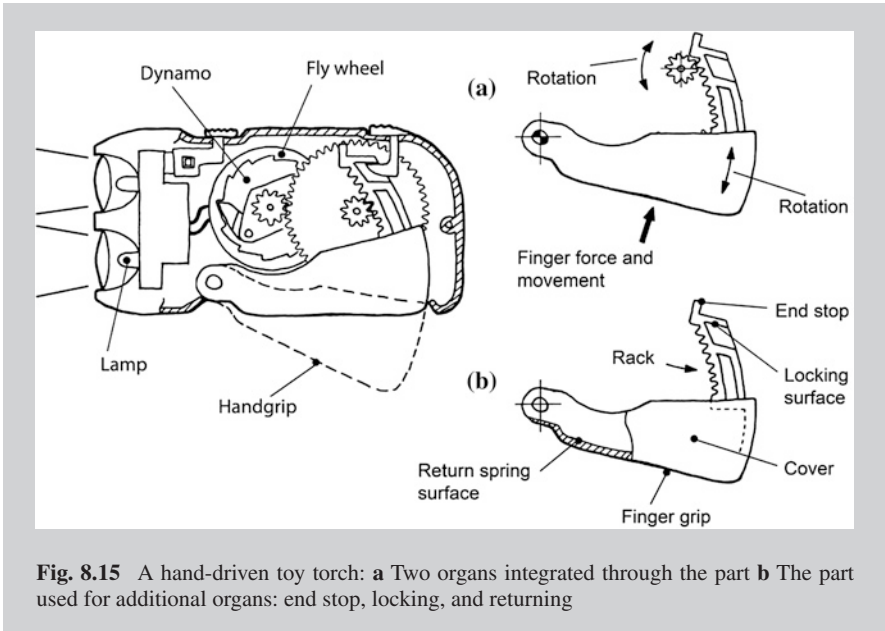
In order to identify parts we need to consider how a product will be created via individual produced and assembled parts. This can be derived from the organs (which are themselves determined by the desired functions). As such, the part structure is primarily dictated by the organs but also takes into account how the product will be manufactured. This composition of parts, or part structure, is also referred to as architecture in the US. For clarity, we use the following definition.

Definition: From an embodiment viewpoint a product is a **system of parts**. This **part structure** consists of parts, seen as elements, and their assembly interfacing, seen as relationships.

This is illustrated in the example below.

Example:

Toy torch. The toy torch in Fig. 8.15 can be viewed from both the organ and part perspectives. In image (a) we see the organ for transmitting the finger forces (the housing also belongs to this organ) and the organ for creating rotation. In image (b) we see the finger grip part and how its details contribute to the organs: for returning, for end stop, and for locking. As such, this one part integrates the two main organs as well as contributing to other organs through its additional features.



A key challenge for designers thus lies in successfully merging conditions from the organ domain with those from the part domain to make an integrated part structure. In this context each part can have multiple modes of action, contributing to multiple organs, and have many of its physical characteristics determined by production and assembly.

Example:

Electric lighter. An electric lighter based on a piezoelectric crystal creates an electrical spark to ignite the gas when a force is applied to the crystal. As such, the crystal is a single part, which requires another part to act on it in order to generate the spark, as well as a circuit leading the current to where the spark is delivered. Here, the crystal is a component specific to the lighter, while the housing and fuel delivery parts are generic to the whole range of lighters produced by the company. This is how the ‘create current’ organ works.

Certain parts and compositions of parts are found identically in many products and therefore available as off-the-shelf products or standard components (machine elements). Compositions may be defined from production point of view as sub-assemblies or from development point of view as modules in product family architectures. Some parts are serving specialized tasks, for instance, where the part is

active as a tool in an activity: The sewing machine's needle, a scissors' two sharp edged parts cutting paper, the propeller giving propulsion to a boat, etc. Such parts normally serve or realize organs operating directly on the activity's operands.

In particular, parts and sub-assemblies are often designed such that they can be used in multiple different products to form either off-the-shelf products or parts of larger product family architectures. Where parts are specialized for a particular product they often realize those organs operating directly on the activity's operands as illustrated below.

It is important to try and articulate an organ's mode of action, as well as precisely define a part's characteristics. From the organ perspective we might ask in which direction the lighter actuator (see above example) must transfer force and how it moves with regard to the desired degrees of freedom. From the part perspective we might ask what form should the actuator take to fit in the operator's hand and interface with the rest of the lighter. These two perspectives are merged in the following part characteristics developed from Hubka (1973):

- **Form** which can be modelled or interpreted as geometry
- **Material**, which determine properties like elasticity, strength, conductivity, etc.
- **Surface quality**, which determine properties as wear, smoothness and reflection.
- **Dimension** in the meaning size and measure; slightly unsystematically can **tolerances** be seen as dimension also.
- **State** like tension, magnetic, warm, etc. necessary for its task in the organs.

In order to complete the part structure it is also necessary to take into account the relationships between the parts, e.g. positioning, fixing, and movability (rotation, sliding). This is generally achieved via the addition of specific **interface** surfaces, e.g. threads, grooves, and chamfers.

Traditionally, the output from this product synthesis process is a set of drawings specifying the parts characteristics as well as how they are assembled. These use a standardized language for projections, cross sections, symbols, etc. However, these only give a partial explanation of the design: we cannot see the liquid in a pump, the current in a circuit, the actions of the user or the use activity when applying the product. As such, we need to more closely consider the overall synthesis of the part structure.

8.7.1 Conceptualization and Models in the Part Domain

When developing the final product it is important to remember that most models or representations of the design are evolving and do not generally describe the final model that will be brought to market. This is important because design is recursive, i.e. we find the same pattern of activity on all levels of the design's resolution into main functions, sub-functions, and so on. However, all these levels

relate to the organs and parts. As such, the designer may use the same concept synthesis and product synthesis operations again and again. Thus, these evolving models allow the designer to flexibly bring together the three domains in an iterative evolution of the final product. This is exemplified by the fact that the visual elements are often the last to be considered. For example, the overall **visual impression** of the product emerges late in Tjalve's development of the Tea machine seen in Fig. 8.17. This stems from the need for an overall understanding of the major parts before aesthetic form can be defined. This means that in incremental design it is often possible to start with a visual design, into which the organs and parts are forced to fit. This is also related to the use of **pattern thinking** in the design to create similarities in a family of products, giving a visual identity and style to support a brand. Similarly, **modular design** aims to create a varied product family by combining common modules. This can give a high level of diversity whilst retaining visual and functional commonality between products.

Alternatively, developing new concepts for parts can create different product solutions. Here, the manufacture of the product incurs significant cost and is therefore worth optimizing were possible. A second alternative is **structural variation**, which changes the spatial position of organs and parts, and varies their interfaces. This can again be undertaken from different perspectives, such as optimizing the product structure or reducing space and material use. These can all be realized using **building method thinking** to support the choice of production method. If we consider, for example gearboxes, door hinges, bicycles, and wristwatches, we find that there is a limited set of preferred alternatives. As such, it can be highly beneficial to start with a known building structure, instead of trying to be innovative in such a constrained environment.

8.7.2 *Spelling the Parts*

The part domain concerns the product's realization: how can we produce and assemble parts so that the overall functionality is achieved? Conceptualization proceeds from abstract considerations about need, use, functions, and organs to parts, but it is also possible to reason from given components. The argument for the longer reasoning path via functions and organ domains is that it allows the possibility of innovation and utilizes all the design degrees of freedom. Further, it ensures a more systematic fit between need, task, and solution. However, in order to be successful it is necessary to remember the parallel need for clarification activities in conjunction with the synthesis of the design. The many choices made in embodiment are based on argumentation that needs documentation in order to support a company's future development, as well as for legal reasons.

The composition of clarification activities is just as complex as the product's exploded view. However, it is not obviously visible and thus easily forgotten.

Our treatment of the part domain may give the impression that synthesis is just completing a jigsaw puzzle with a mix of new and reused pieces. It looks like this because we have not discussed the need to create the product's goodness as part of the synthesis. This goodness comes from attractive functionality, fulfilment of the required properties, and a balance between quality, cost, manufacturability, and sustainability.

8.8 Product Synthesis: A Three-Domain Progression

Proposals for how to progress with Product Synthesis are rare outside of concretization and detailing of the part structure. Here, the conceptual core can come from many different areas, e.g. new business ideas, a novel way of using an existing product or new features of organs. However, whichever path is chosen there are certain characteristic patterns that describe the progression of the design activity. One major example of this is that the significance of decisions follows two defined progressions. First, the significance rapidly decreases from the early stages where quality of need satisfaction and business cases are considered. Second, the detailed decisions become more important towards the end of the process with the increasing importance of quality and, e.g. manufacture of the product. These two curves describe the importance of keeping focus on both the need satisfaction and business matters, and the details of realization (Andreasen and Hein 1987), illustrated in Fig. 8.16a.

A second characteristic is the start and finish of design. Here, the end is given by a fully specified part structure, ready to go to production. In contrast, the start can be found in any step, although the causality chain must be respected. For example the use activity's result satisfies the need > realized via the use activity > facilitated by the product's effects and functions > delivered by the products organ structure > and materialized in the part structure. We call this a causality chain because each level's goal is defined by the level above, as illustrated in Fig. 8.16b.

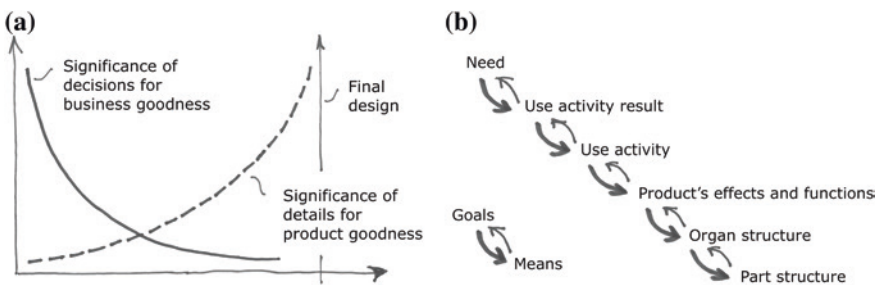


Fig. 8.16 Two characteristic patterns of product synthesis: **a** the importance of decisions **b** the causal chain

This causality chain is not articulated in the literature except by Hubka's General Procedural Model of the design process (1976) and implicitly by Tjalve (1979). However, Tjalve does give an exemplary articulation of product synthesis beginning with problem analysis. Tjalve takes four further steps: function thinking, search for solutions, defining the basic structure, and the quantitative structure. These steps are illustrated in Fig. 8.17. **Basic structure** describes organs and

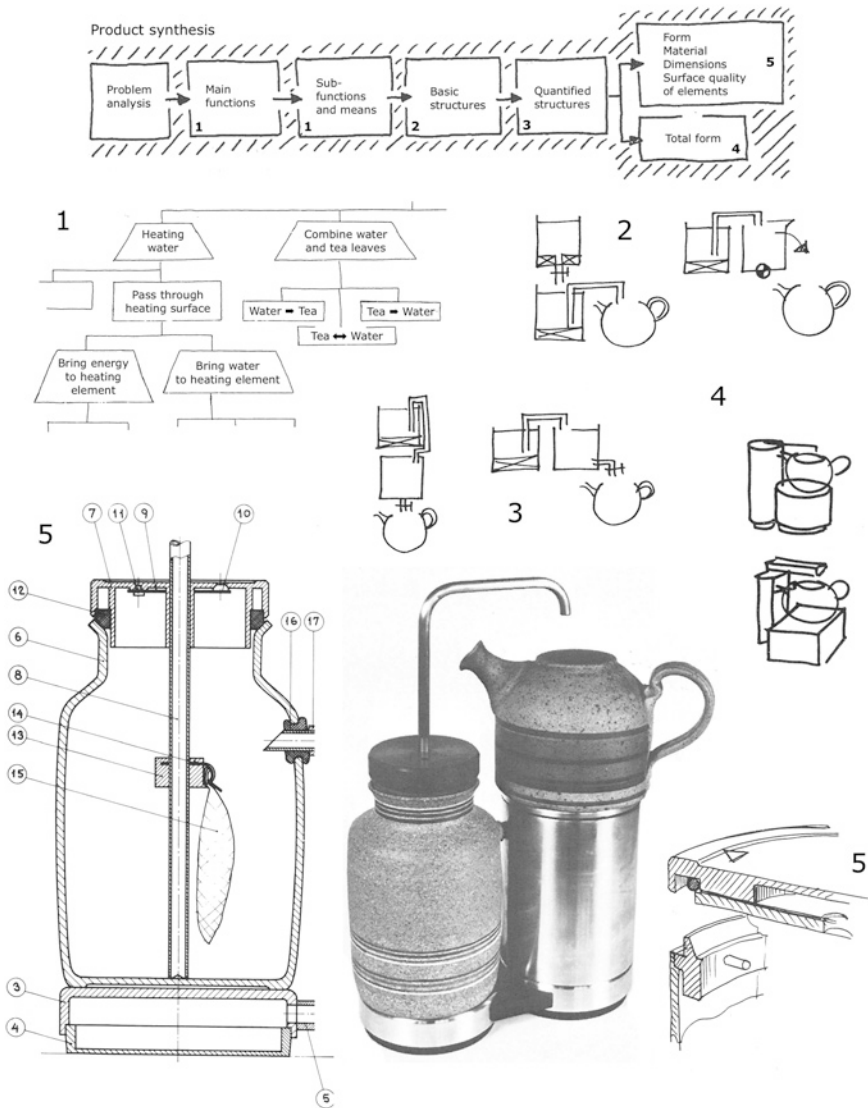


Fig. 8.17 Product synthesis as proposed by Tjalve (1979), illustrated using a copy of Tjalve's figures of the design of a tea machine. The numbers of the sketches refers to Tjalve's model of product synthesis at the top

their functional relations giving the principle of the product. Here, alternative solutions or combinations lead to different basic structures. **Quantitative structure** describes the transition from organ to part structure. The organs physical volume and physical interactions are determined, and alternative spatial structures are considered. These determine the operation of the product, production, assembly, and installation.

8.8.1 Top Down or Bottom up?

Product synthesis models mirror the artefact's nature. For example Tjalve's model generally points to many of the design degrees of freedom that also exist in the design of non-mechanical products, while most models from literature concern mechanical products. All these models describe a *top down* sequence of activities from a functional perspective, where the authors note that feedback loops may occur. These models tend to be visually sequential with the feedback loops or derivations from the sequence poorly described. However, as we saw in Chap. 5 these loops are almost unavoidable because of co-evolution and intrinsic features of design. For example co-evolution shows how increasing insight into possible solutions gives better insight into the problem and thus forces the designer to refine their approach. We explore some of these issues in the following example.

Example:

Egg sausage machine. In the late 1960s a Danish egg producer came up with the idea of producing hardboiled egg in the form of a sausage. The aim was partly to deal with the needs of its catering business and partly to better utilize its raw materials in producing a refined product. Hubka and Andreasen worked together on the development of the machine. After a number of unsuccessful attempts to find a principle for a continuous process it was decided to use discontinuous forming and coagulation. Here, a set amount of yolk and white were combined and heated, causing coagulation from the outside in. Once this process was complete the forming tube was removed. The end result was an egg sausage that gave well-proportioned identical slices. This is illustrated in Fig. 8.18.

Experiments showed that the originally expected machine layout, using a hinged form, was impossible because the white stuck to the form surface. This problem was solved using a spring-form, however, this changed the design of the form parts, demanding a new layout. A second change based on experimentation was that the original concept, with a forming tube surrounded by the heating chamber, was not as simple as first imagined. Here it was found that it was necessary to interrupt coagulation by cooling. As such, cooling chambers were defined and the form with the coagulated sausage moved from

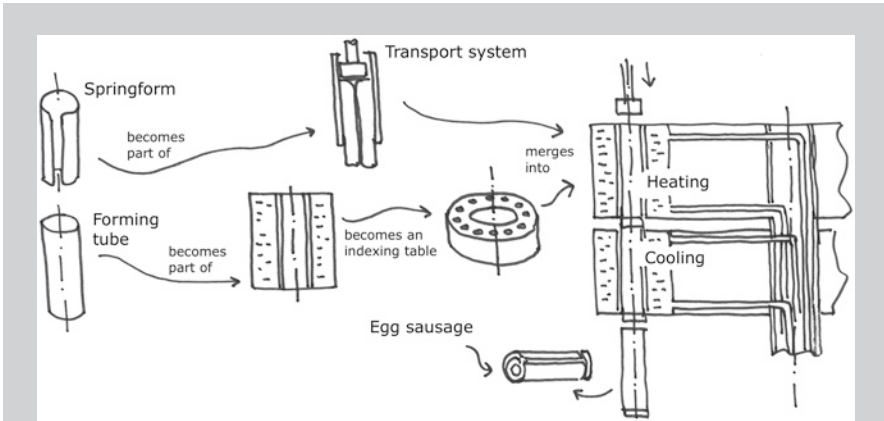


Fig. 8.18 Opportunistic considerations in the design of an egg sausage machine

heating to cooling zone. Finally, in order to achieve the desired level of productivity it was necessary to arrange 48 tube subassemblies in a carousel.

This leads to two realizations. First, something that was originally thought to be a minor detail, the separation of the sausage from the form, ended up being decisive in the machine's layout. Second, the physical realization of the organs via the part structure solved multiple functions. For example, the spring-form not only solved the separation issue but also was also integral to the transport system moving the sausage between heating and cooling zones. Further, the heating and cooling chambers became an integral part of the larger production carousel.

Necessary organ materializations were utilized for the through flow functions: the spring-form becomes a transport system, the form tube becomes part of the heating and cooling chambers and part of the transport system, the heating and cooling chambers become a carousel.

This example shows how detailed considerations can have significant effects on the overall product synthesis and that this is realized by moving between the three domains. This is illustrated in the three parallel activity patterns in Fig. 8.19. In all three domains there is progression from abstract to concrete and from undetailed to detailed. Further, both the satisfaction of the need via the final use activity and the complete specification of the part structure can be seen as end points. This is idealized in the cause chain shown in Fig. 8.16 and the example progression shown in Fig. 8.19.

Many factors influence the design of the product. Broadly speaking any single factor or issues can form the basis for new product conceptualization. A typical example of such an influential issue is sustainability. A company may see redesign for sustainability as an opportunity to develop a more sustainable brand image and increase its market share. However, sustainability can be linked to almost 'everything' in the company, e.g. product range, suppliers, manufacture, product life

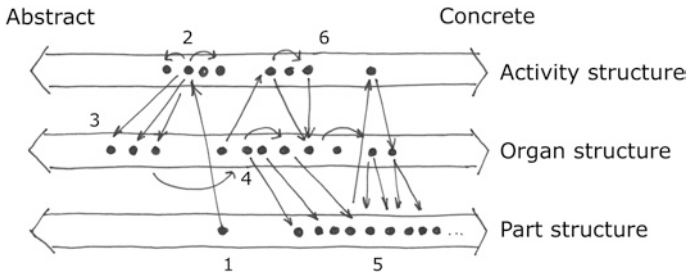


Fig. 8.19 Interrelation between the three domains in a product synthesis case. The *arrows* illustrate the progression from the egg sausage example: 1 spring-form > 2 activity considerations > 3 sub-system functions and 4 organs > gradual detailing of new sub-activities 5 and new organs 6

aspects, and material consumption. Thus, it is up to the company’s ecological conscience and its creativity to select a focus area and perform innovation.

We postulated a “three domain progression” as being a fruitful understanding of product synthesis in this section. Although this can seem complex it is a recognition that all three aspects need to be considered if freedom and potential solutions are not to be lost. As such, we propose some heuristics to help the designer with this progression.

There is no reason to follow or expect a strict sequence in the product synthesis activity. It can be much more powerful, in terms of innovation and value creation, to be able to fluidly focus on ideas in each domain as they arise.

Even though *Exploration* and *Concept Synthesis* create the ‘conceptual core’ it is never too late in product synthesis to add new dimensions if they enhance the product, value or business. These can also reveal new perspectives and thus change the conceptual core.

Product synthesis takes different forms depending on the type of design being undertaken. For example consider the three types introduced in Chap. 1: new, incremental, and platform. In **new product design** synthesis is dependent on Exploration and Concept Synthesis for confirming the need is valid and for ensuring the tractability of the innovation project. In **incremental design** past designs are used as a starting point and thus substantial contextual and design information can be brought forward into the new product. However, this should be balanced against a strong description of the new product concept, ensuring it has a *raison d’être* in and of itself. Finally, in **platform-based design** each relevant product variant belongs to a family of products. The definition of variation and commonality between the family members is designed to ensure broad market coverage, as well as good utilization of company assets. Thus, the individual product is bound to certain game rules, dictated by the characteristic activities, organs, and parts, associated with the product family.

8.9 Product Modelling: The Product's Chromosome

Many models are created during the design activity, each with different purposes and techniques as discussed in Chap. 3. As many of these models relate to the synthesis of the design we propose the following distinction:

- **Design models:** intermediate models that support synthesis, communication, and verification activities via, e.g. simulation.
- **Product models:** models that support the progression and final specification of the design via, e.g. technical drawings for manufacturing purpose.

Roth (1988) noted that many partial models, not necessarily linked to each other, characterize design work. Figure 8.20 illustrates how design activity can be seen as levels of functional decomposition leading to a growing number of related models, and how Roth's imagination of scattered models might look. In order to bring these views together we developed what could be seen as a genetic design model system (Mortensen 1999). As proposed by Ferreirinha et al. (1990) we call this core product-defining model a Chromosome Model, shown in Fig. 8.21. The Chromosome Model is intended to give a generic descriptive model of the product, mirroring Domain Theory. The composition of activities, organs, and parts is modelled in hierarchical patterns and interrelated as shown in Fig. 8.21. The model has gradually been changed (Andreasen 1990; Jensen 1999; Mortensen 1999). As

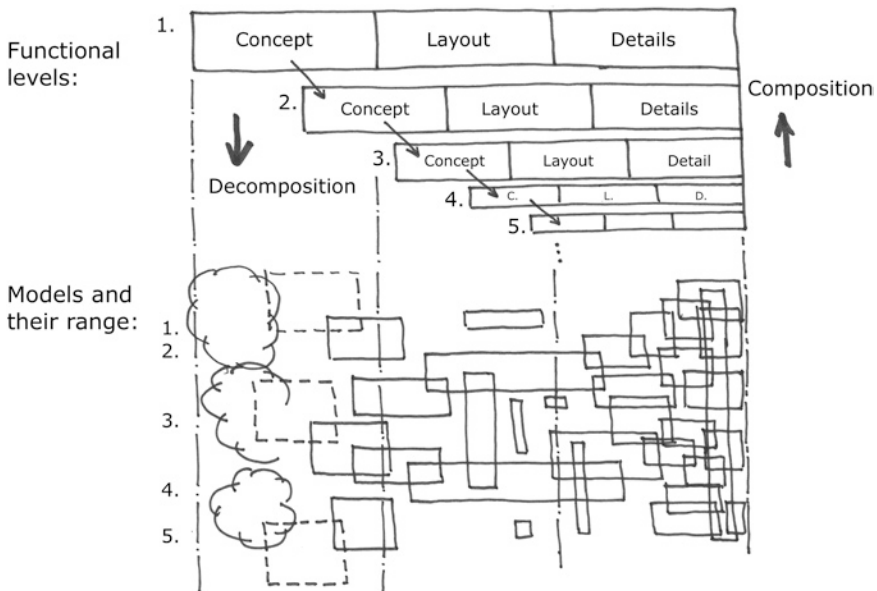
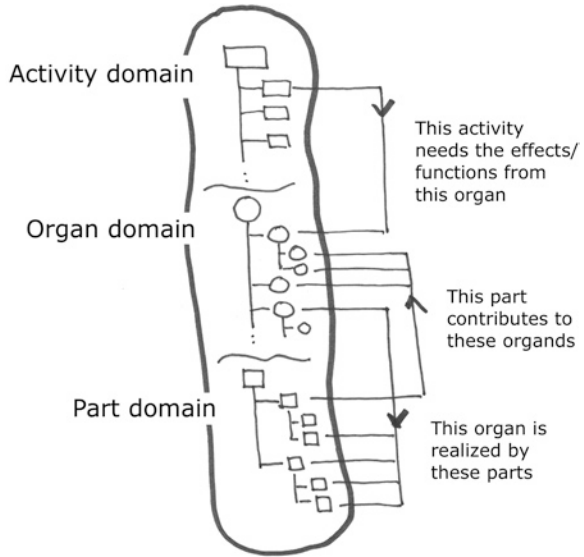


Fig. 8.20 A scattered pattern of design models in product synthesis. The *top picture* shows the top-down determination of functions and synthesis, while the *bottom picture* shows Roth's description of scattered models in time and coverage

Fig. 8.21 The chromosome model



such, the model captures the gradually synthesized design entities. When we want to clarify a certain sub solution we may sketch and detail it in a design model until its characteristics can be added to the overall product model.

In contrast to clarifying a certain sub solution we can explore and justify certain properties of the design via a view model. This is composed of the design characteristics, parameters related to the surroundings and the influences (stimuli). Figure 8.22 shows these relations with respect to the product model and other intermediate design models.

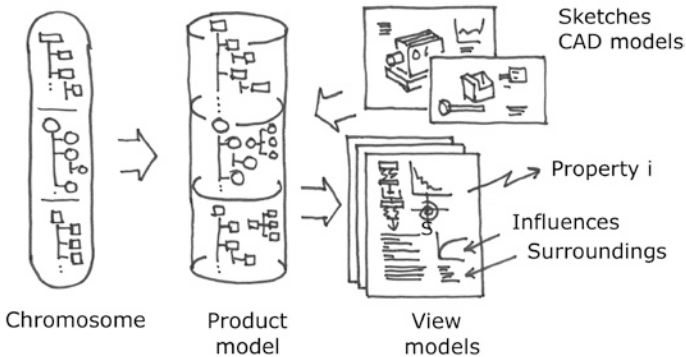


Fig. 8.22 Ideal application of the chromosome model for creating a structural product model in the three domains. The product model gradually builds up from design considerations and delivers characteristics to view models of certain properties

Definition: A **view model** is a model derived from the product model able to articulate a certain product property.

In order to work effectively there are three major preconditions for these models functionality:

- **Design language**, i.e. a vocabulary for thinking, reasoning, conceptualizing, and specifying solutions in all three domains based on semantics and syntax. This should be applicable for human reasoning and computer operations.
- **Design models**, i.e. models for structures of activities, organs, and parts, carrying the specification of these structures. This also allows for more or less formalized specification of the relationships inside and between domains, as well as the property statements of entities.
- **Design operations**, i.e. methodologies to support gradual synthesis in all domains, e.g. via methods for synthesizing, composing, evaluating, and simulating.

The application of the Chromosome Model's structure in the definition of the product means that the following basic views are present in the design of the product: Its use activity, its functionality (described by the organs), and its embodiment (described by the parts).

8.9.1 Applying Product Synthesis Models

Domain Theory is a model-based theory, which means that it is based on words and concepts taken from the description of the domains and the phenomena related to the domains. However, other concepts are also plausible and therefore we find several other proposals for models of product synthesis (Pahl and Beitz 2007; Hubka 1976; French 1985; Pugh 1991 and many others). What we think is most important for a designer though, is how productive a theory is when used in practice.

The concepts outlined in this chapter have been chosen because they have shown time and again to be highly relevant and useful in practice in, e.g. conceptualization, Design for X, dispositions, modularization, and platform thinking. Further, because modules are both linked to organs and composed of part domain entities Domain Theory is very suitable for supporting design reasoning (Chap. 11) and modelling modular systems (Mortensen 1999; Harlou 2006). We return to the some of these topics later in this book, including the view model and property reasoning in Chap. 12.

8.10 Conclusion

The module ‘Product Synthesis’ is the design activity we find described in the textbooks as engineering design. Our approach here is to use Domain Theory as the basis for explaining, modelling, and articulating the design process. This leads to a pattern quite different from traditional ‘sequential’ engineering design models, rather Domain Theory provides the basis for ‘spelling’ the product. This theory has shown its worth in a large number of industrial modularization and platform projects, as well as in supporting new design and management procedures in many Nordic companies.

In Chap. 3 we introduced Cross’ ‘designerly ways of knowing’ and the ‘constructive mode of thinking’ as core characteristics of design. In complement to this we see Domain Theory as articulating basic constructive traits of designing, i.e. the need to consider the three views, each with their own properties but all necessarily integrated in the final design. Thus, product synthesis is based on theories about the nature of products and the relationships between activities and products. As such, Product Synthesis encapsulates Exploration and Concept Synthesis in a development project, practicalities and the nature of the project determine what is most appropriate. In the following chapters we encapsulate Product Synthesis in the larger modules, Product Development and Product Life Synthesis and thus add the organizational conditions for utilization and realization of Product Synthesis’ results.

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