Design research programs and the logic of their development

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DESIGN RESEARCH PROGRAMS AND THE LOGIC OF THEIR DEVELOPMENT

ABSTRACT. Design research programs attempt to bring together the properties of available materials and the demands derived from intended applications. The logic of problem states and state transitions in such programs, including assessment criteria and heuristic principles, is described in settheoretic terms, starting with a naive model comprising an intended profile and the operational profile of a prototype. In a first concretization the useful distinction between structural and functional properties is built into the model. In two further concretizations the inclusion of potential applications is motivated and described for the case of drug research as well as the inclusion of potential realizations for the case of complex products. Next, another line of concretization of the naive model, the incorporation of potentially relevant properties, is sketched. Then the partial analogy between "product-" and "truth-approximation" is indicated. We conclude with some remarks about the usefulness of our models for products reaching the market in comparison to the the so-called social construction of technology approach.

1. DESIGN RESEARCH PROGRAMS

The notion of a research program has proved to be useful for the description of scientific developments. As is well known, Lakatos has characterized a research program in terms of a hard core of ideas and a positive heuristic, i.e., a set of heuristic ideas, e.g. generated by a model, to protect the core ideas against serious attacks. In our opinion there are many research programs that don't have a stable positive heuristic, but are nevertheless successful. Hence, we speak already of a research program when there is a hard core of ideas, "ideaprograms" to be precise.

Of course, research programs are supposed to deal not only with a certain domain of phenomena but also with a certain type of problem about this domain. From the literature it is clear that at least three types of problems occur. There are research programs that are primarily *descriptive* or experimental: they are directed at a description of the domain, which may or may not be based on experiments. Other research programs are primarily *explanatory* or theoretical: they are directed at an explanation of general or individual facts of the domain. Besides these empirical research programs there are also conceptual research programs, in particular *explication* programs: they are directed

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at the construction of an elegant, relatively precise and useful concept starting from an informal concept.

It is certainly possible to describe large parts of scientific research in terms of descriptive, explanatory and explication programs and their interaction, i.e., competition or co-operation. However, there are also many research programs which do not fit very well in one of these prototypes or a combination of them. For example, research programs directed at the design or construction of new materials, of medical drugs, of growing methods for agricultural products, of expert systems and other AI-systems, of new psycho- and behavioural therapies, etc. Hence, such research programs are directed at the design or construction of certain products or processes which have to satisfy previously determined demands and these demands are based on the intended applications. For brevity, we will speak of products, also when processes are meant or the improvement of already existing products or processes. The hard core of such programs is frequently called the "lead": the basic idea about how the product is to be composed or how it has to work.

In view of the fact that this type of research programs occurs not only in the natural and technical sciences, but also in the social sciences and the humanities, we do not like to speak of technological research programs and prefer to speak of construction or *design* (research) programs: their internal goal is the actual construction of the intended product, which is based on one or more intended applications.

2. THE LATTICE MODEL OF WEEDER C.S.

The problem of how design programs develop itself asks for a descriptive research program at the meta-level. In 1982 Pieter Weeder and Do Kester published a paper in Dutch which we like to consider as the start of an important ideaprogram in this respect. Some other members of the Science Studies Unit of the University of Groningen had been involved in the first development of the idea and the case study, viz. the Tenax project of the Akzo laboratory in Arnhem (Netherlands), in particular Philip Vergragt and also Henk Bodewitz and Gerard de Vries. Not earlier than 1988 the first English (improved and extended) version appeared, written by Henk Bodewitz, Gerard de Vries and Pieter Weeder. Given that Weeder was the only common author we speak of the descriptive program (and the lattice model) of Weeder c.s.

In characterizing the development of a descriptive program we have to make a distinction between the core idea on the one hand and the resulting description on the other. A similar distinction can be made for explanatory programs, roughly the explanatory idea and the resulting explanation. The present paper intends to contribute to the further development of the core idea of Weeder c.s.. A first formulation of this core idea is the following:

Core idea: The development of design programs can best be described as a more or less systematic attempt to bring together the properties of the available materials and the demands derived from the intended applications.

This core idea is specified in terms of a so-called lattice model and it is convincingly illustrated by the Tenax case that the core idea is indeed very illuminating as the basic perspective for its development. Theoretically it is shown to give rise to a plausible cyclic structure of the R&D process in which a number of well-ordered strategic decisions play a crucial role. Finally, an interesting relation is suggested between the present type of analysis of the R&D process at the laboratory research level and the ideas on technology and technological innovation which are laid down in the evolutionary theory of economic change by Nelson and Winter.

For all this the reader is referred to the mentioned paper of 1988. The present paper only intends to improve upon the specification of the core idea, claiming that the new model throws more light on "the logic of problem states and transitions" in design programs. The informal lattice model of Weeder c.s. does not enable to use some standard formal description technics, whereas our model enables to use the technics of elementary set theory. In order to motivate our settheoretic model we start with quoting the concise presentation of the lattice model in the 1988 paper.

"Defined in broad terms, the aim of research and development in industrial laboratories is to contribute to the design of industrial products with technical characteristics which meet the purposes, desires and explicit requirements of customers as these are perceived within the

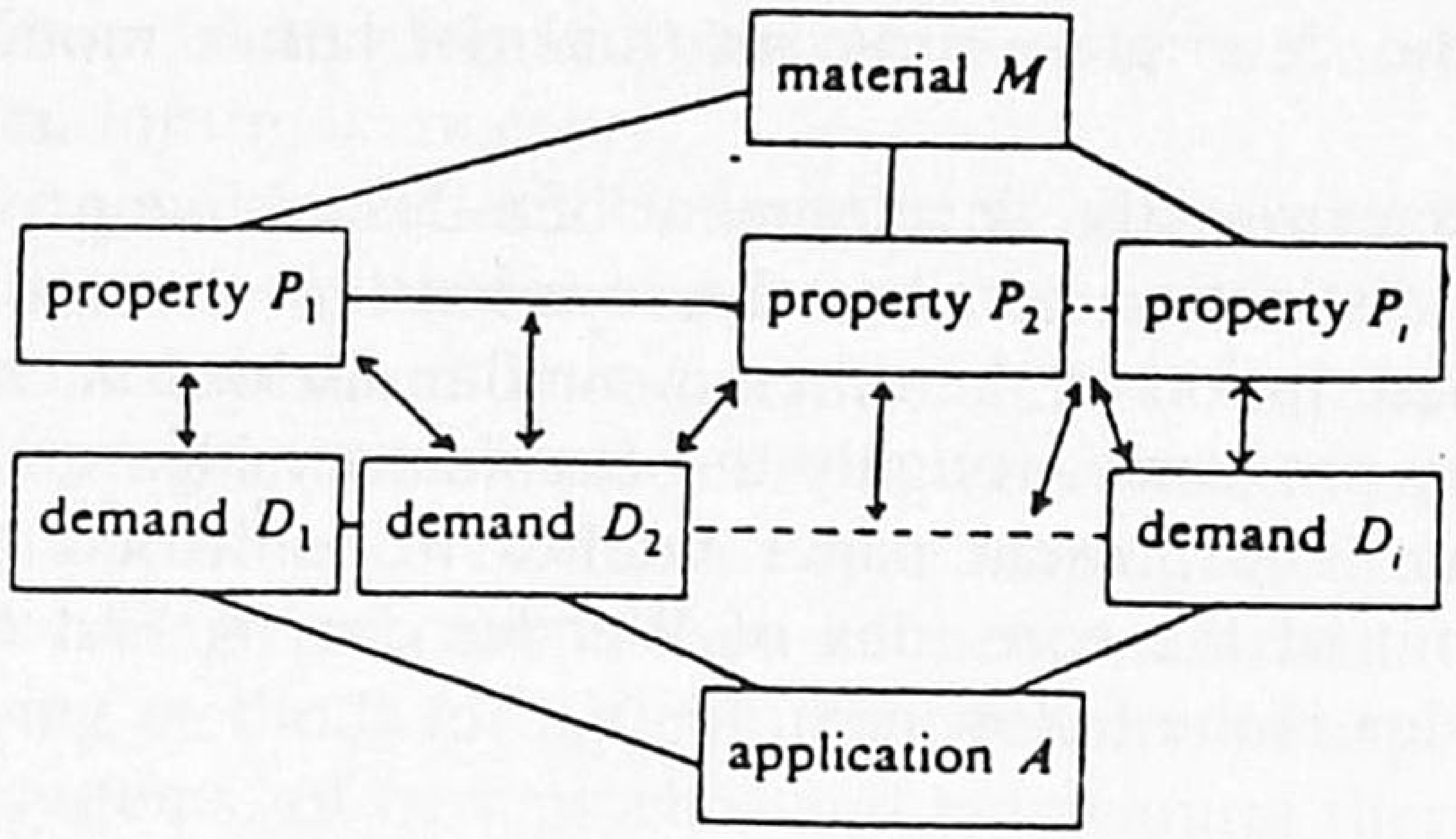

Fig. 1. The lattice of properties and demands.

firm. Consequently, we may view the R&D process as involving two sets of data, viz.

(1) the set of *materials* or classes of materials with certain relevant *properties*, especially of a physical-chemical nature;

(2) the set of *intended applications*, or tasks, incorporating technological and economic *demands*.

In an elementary form, the R&D process may be conceived of as an attempt to match these two sets, aiming at a product which materializes the intended applications.

Visually, the matching process may be represented in a "lattice", in which the research task consists in attempting to connect the set of demands D_i of an application A with the set of properties P_i of material M. Of course the properties are mutually dependent. The same holds for the demands D_i (see Figure 1)."

It is precisely the figure that shows immediately that it is difficult to visualize states and to assess state transitions such that "the logic of the problem situation", to use Popper's favourite term, comes to the fore. The main cause of this lack of transparency stems in our opinion from the fact that two quite different intuitions are mixed in the property/demand-terminology, not only in the formulation of the core idea but also in the lattice model specification of it. On the one hand there is the distinction between the factual properties of the already available product and the desired properties of the intended product. On the other hand there is the distinction between technical or structural properties and service or functional properties, irrespective of whether they are factual or desired. The two distinctions are clearly of quite a different nature, they are perpendicular to each other. However, it is clear from the quoted passage that these distinctions have not been disentangled in the lattice model. In this paper we will show that the first distinction, between factual and desired properties, is the clue to the logic of the situation. Of course, the second distinction is also of fundamental importance, but it is to be introduced as a concretization.

3. THE NAIVE (SET-THEORETIC) MODEL

Problem States

Let RP indicate the set of *relevant properties* for the product to be developed. For each element of RP it is assumed that its presence or absence is explicitly required in the specification of the intended product. Let the subset W of RP indicate the set of *wished for properties* of the intended product; W will be called the *intended profile*. Of course, $RP–W$ is the set of unwanted properties.

For each concrete candidate product x, henceforth called prototype x, it is important to determine which properties in RP it actually has. Let the subset $O(x)$ indicate the set of these factual or *operational properties* of x; $O(x)$ is called the *operational profile* of x.

The problem situation in a certain state of development can now clearly be depicted in Figure 2, viz. the fact that the two profiles don't coincide: the problems consists of the two starred sets, $W–O(x)$ and $O(x)–W$.

$W–O(x)$ represents so to speak the unrealized "positive" desires, and $O(x)–W$ the realized "negative" desires.

Let us introduce the plausible basic formal notion for comparing any pair of profiles P and P^*, i.e., any pair of subsets of RP. It is the so-called *symmetric difference* $P \Delta P^*$, defined as the union $(P - P^*) \cup (P^* - P)$. $P \Delta P^*$ indicates an elementary type of qualitative distance or dissimilarity between P and P^*. Hence, the smaller it is, the greater the similarity between P and P^*.

At certain occasions it will also be attractive to have quantitative formal notions, in which case we have to assume that RP is finite, or at least all profiles to be considered. $|P|$ indicates the number of elements in P, hence $|P \Delta P^*|$ is a quantitative measure of the dissimilarity of P and P^*.

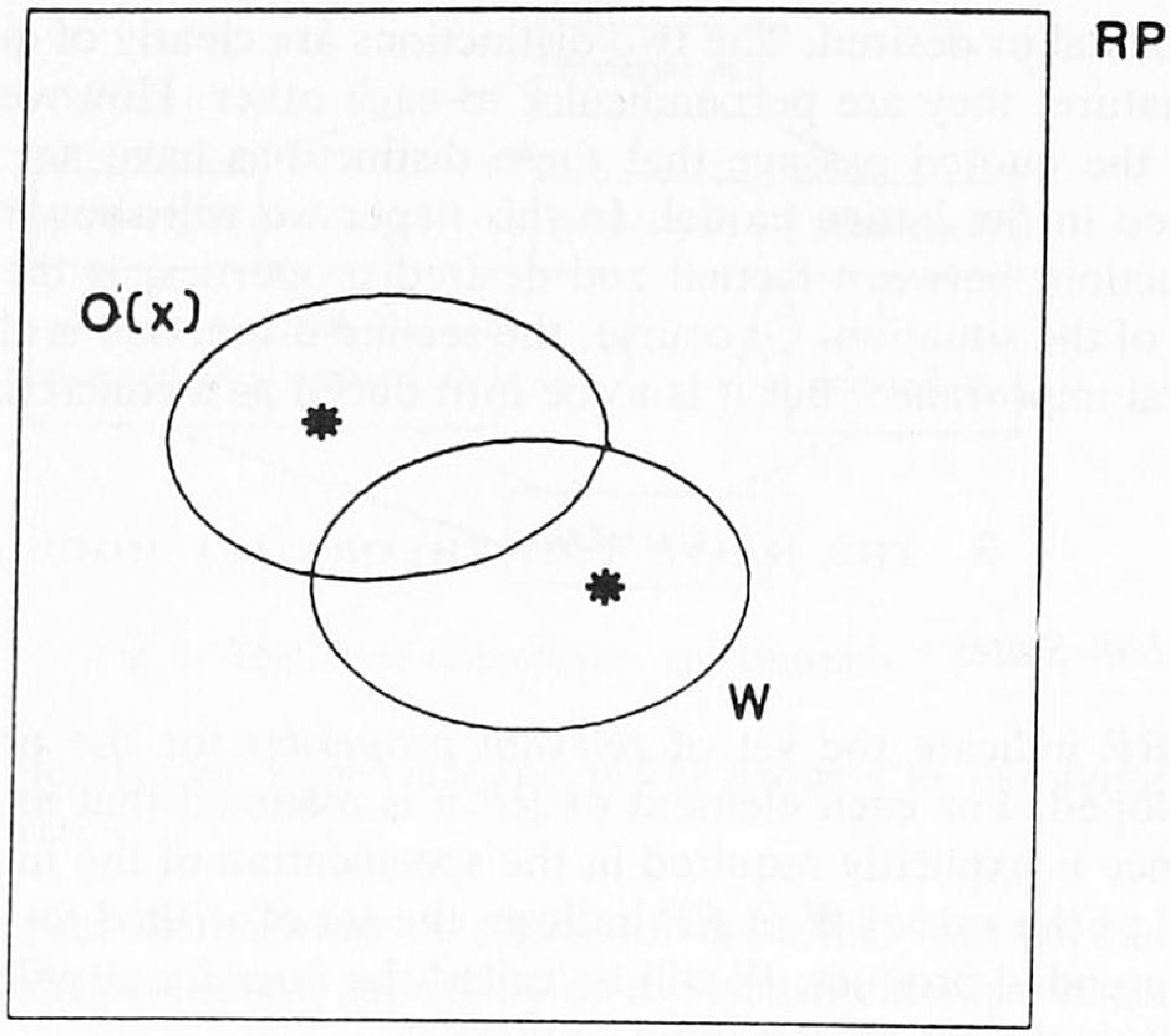

Fig. 2. A problem state.

By consequence, $O(x) \Delta W$, the union of $W–O(x)$ and $O(x)–W$, the starred areas in Figure 2, represents the problem state in qualitative terms and $|O(x) \Delta W|$ in quantitative terms. More precisely, $O(x) \Delta W$ specifies the set of problems, i.e. the deviations from the claim that $O(x) = W$, and $|O(x) \Delta W|$ represents just the number of problems, i.e., the number of deviations.

Transitions of Problem States

$O(x) \Delta W$, indicating the set of problems of the problem state, forms the starting point for negotiation, the set of negotation options, about what to do: trying to change x into some x' such that $O(x')$ becomes more similar to W, or changing W into some W' such that W' becomes more similar to $O(x)$, or both.

It is plausible to give a formal characterization of certain transitions of one problem state into another by the following definitions, which form the cornerstones of the present paper ("$\subset$" is the sign for proper subset).

DEFINITION 1: (a) Prototype x_2 is a *qualitative improvement* of x_1 in view of W iff $O(x_2)\ \Delta\ W \subset O(x_1)\ \Delta\ W$.

(b) it is a *quantitative improvement* iff $|O(x_2)\ \Delta\ W| < |O(x_1)\ \Delta\ W|$.

DEFINITION 2: (a) Intended profile W_2 is a *qualitative concession* to prototype x compared with W_1 iff $O(x)\ \Delta\ W_2 \subset O(x)\ \Delta\ W_1$.

(b) it is a *quantitative concession* iff $|O(x)\ \Delta\ W_2| < |O(x)\ \Delta\ W_1|$.

These definitions provide the basic assessment criteria for state transitions. The first definition enables us to evaluate potential improvements of the prototype, i.e., transitions from one prototype to the other in the face of a fixed intended profile. The second definition specifies how to evaluate potential concessions, i.e., transitions from one intended profile to the other in the face of a fixed prototype.

The first type of transition is an answer to one particular specification of the problem state, viz. how to bring the prototype closer to the intended profile? The second type of transition is an answer to the remarkable conversion of this problem specification, viz. how to bring the intended profile closer to the prototype? That this problem specification is realistic is documented in Vos (1991) and hinted at in the title of that book: *Drugs looking for diseases*.

It is evident that in both cases the qualitative judgement implies the quantitative one, but not the reverse. The quantitative definitions are so rough that they even lead to linear orderings for prototype and intended profile transitions. However, the qualitative definitions obviously lead only to partial orderings of both types of transition. But from the formal point of view they represent the purest cases. They are depicted in Figure 3 where in both cases the two shaded areas are empty and at least one of the two starred sets is non-empty.

Some remarks about constraints for the domain RP of relevant properties have to be made. It is clear that there is no reason to have both a property in RP and its counterpart: if for example "flexible" belongs to RP, and W or $O(x)$ is supposed to contain "non-flexible" one simply excludes "flexible" from W or $O(x)$, respectively. This avoidance of duplication is even an advantage in that it restricts the formal constraints on profile pictures. An equally inconvenient formal constraint can be avoided by excluding the occurrence in RP of the combination of two properties in RP as a new property. If we would not exclude a combi-

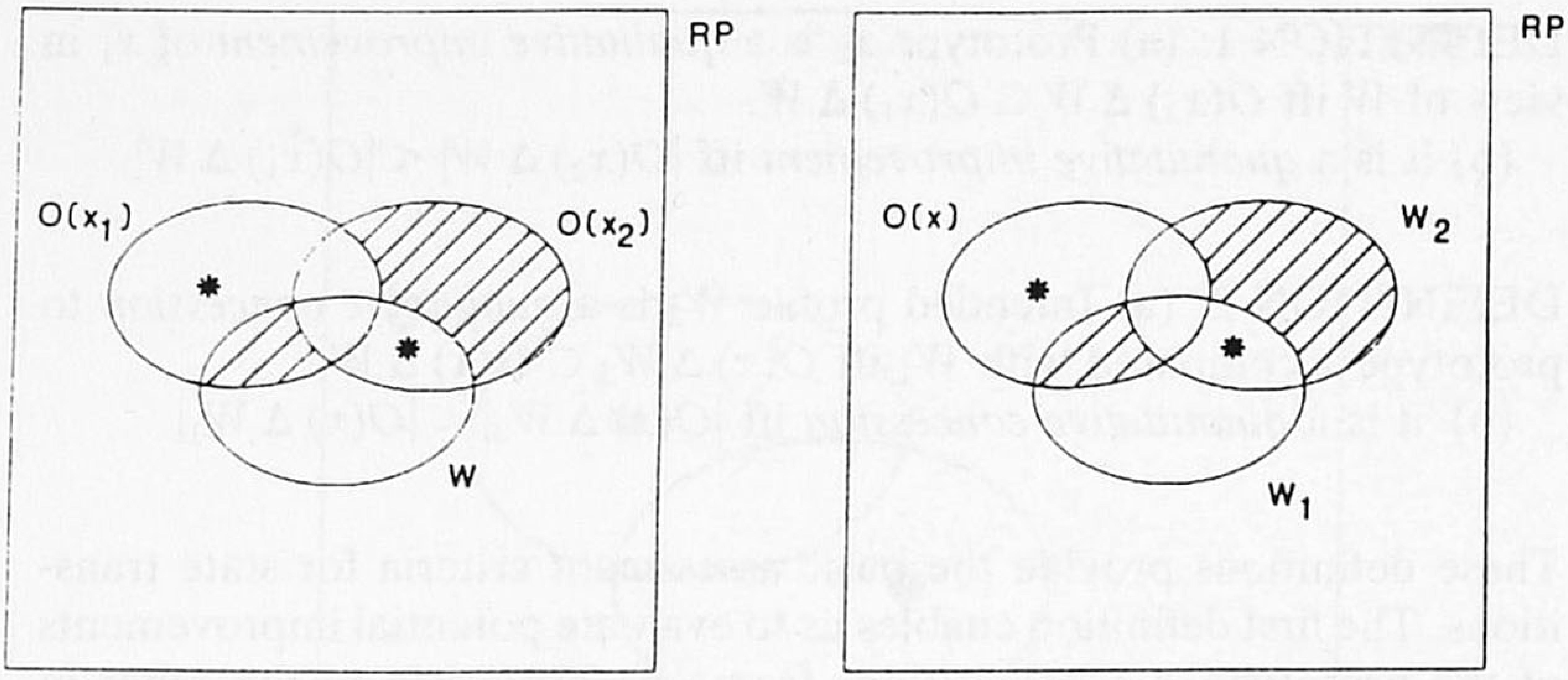

Fig. 3. A qualitative improvement of a prototype (left). A qualitative concession of the intended profile (right).

nation of properties as a new property all profiles would have to be closed for combinations. There do not seem to be other plausible restrictions to *RP*. It is important to note that not every subset of *RP* needs to be empirically possible, i.e., not every conceptually conceivable profile needs to be empirically realizable. In other words, there will be all kinds of causal connections between (subsets of) the properties in *RP*.

From the presented point of view the development of a design research program is a succession of problem states, where problem transitions will as a rule be quantitative, and ideally qualitative, improvements or concessions. There may be different types of specific research involved. First there is direct experimental test research involved. For any new prototype x and intended profile W the claim $O(x) = W$ has to be evaluated by experiments. Besides this direct empirical research there may also be involved descriptive, explanatory or explicative research that primarily belongs to other research programs. In terms of Zandvoort (1986), the design program operates as *guide program*, and the others as *supply program*.

Possible Refinements

The presented settheoretic model is a naive model in many respects and its value depends largely on the degree in which it can be concretized to adapt to all kinds of realistic complications. In practice, one or more of the following refinements will be required.

(R1) Instead of having a simple yes/no character, properties usually have to be construed as functions with a range of more than two values, possibly even infinitely many.

(R2) Some properties may be more important than others, without the latter being negligible.

(R3) It is usually not immediately clear whether a property is relevant or not. In the course of product development their relevance may become clear and the different actors in the process negotiate about them.

(R4) In many cases there is a plausible distinction between structural and functional properties, such that the intended profile is primarily specified in terms of functional properties, whereas of the available prototype the structural properties are primarily known.

(R5) In some cases it is very helpful to include a set of potential (intended) applications explicitly in the model, as suggested in the lattice model of Weeder c.s.

(R6) It may sometimes also be helpful to include a set of potential realizations, roughly corresponding to different materials in the lattice model.

Lack of space prevents us to deal with all these refinements here. The first two refinements are essentially technical. Vos (1991) describes in detail how the first refinement can be realized and suggests how to deal with the second. The refinements (R3) and (R4) are of fundamental conceptual importance. The distinction between structural and functional properties (R4) is introduced in Section 4. The importance of the further refinements (R5) and (R6) depends very much on the type of intended product. In Section 5 the set of potential applications (R5) will be included for the case of drug research, viz. diseases. That section, based on Vos (1991), provides at the same time a concise application of our conceptual apparatus. In Section 6 the introduction of a set of potential realizations (R6) for complex products, based on Sie (1989), is presented. The refinement of the naive model with "potentially relevant properties" (R3) will be described in Section 7.

It will become easy to see that the R3-line of refinement is essentially compatible with the R4/5/6-line. Hence the question how they can be integrated may be left as a technical exercise. The same holds for the combination of the technical refinements (R1) and (R2) and the others. In sum, we may conclude to have a network of related models, with the naive model as point of departure and the choice depending on the context.

We like to conclude this section by claiming that the presented naive model of problem states and transitions, conceived as an alternative specification of the core idea of the program of Weeder c.s., is already an improvement on the lattice model. In Section 8 it will be shown that this naive model moreover enables a comparison of the differences and resemblances between design programs on the one hand and descriptive and explanatory programs on the other; to begin with, the former are product directed and the latter are truth directed. Finally, in Section 9 we will make some remarks about the usefulness of our models for products reaching the market in comparison to the the so-called social construction of technology approach.

4. STRUCTURAL VERSUS FUNCTIONAL PROPERTIES: THE S/F-MODEL

In many contexts it is possible and customary to divide the set of relevant properties *RP* into a subset of technical or structural properties *S* at the one side and a subset of service or functional properties *F* at the other. *S* and *F* do not overlap each other and they exhaust *RP*.

We like to mention an example taken from a paper by Saviotti (1988), where he uses the distinction, in his terminology, between technical and service characteristics, as the basis for a description of technology development, i.e., the rise and fall of products or technologies on the market. In the description of aircraft technology there are at the one hand technical properties like engine power, wing span, length, geometry, engine type and at the other service properties like maximum speed, maximum take off weight, range. Note that these properties, in their present formulation, are not of the simple yes/no type, but that is irrelevant for our present purposes. It was Saviotti's paper that inspired us to use the same distinction in the description of the process of product development, but we prefer the more general terminology of structural versus functional properties.

It is plausible to call $O(x) \cap S$ the *operational structural profile* $OS(x)$ of prototype x and $O(x) \cap F$ the *operational functional profile* $OF(x)$. Of course, it follows that $O(x) = OS(x) \cup OF(x)$.

It is also possible to make the same division in the intended profile W: the *wished for structural profile* WS and the *wished for functional profile* WF. But it is not evident that the latter distinction is also realistic. It suggests that we specify W beforehand, with the consequence that WS is simply equal to $W \cap S$ and WF equal to $W \cap F$. In practice it is usually the other way around. As a rule, WF is provisionally determined first, for we start by asking what the product is supposed to do in the intended applications. As soon as we have fixed WF the next question is how WF can be realized. It is of course not guaranteed that there is just one subset of S causally implicating precisely these functional properties. In other words, there need not be a unique WS, we have to leave room for "functional equivalents". We will call a set of structural properties *appropriate*, or an *appropriate structural profile*, for WF if it causally implies WF. Such a set will be indicated by $AS(WF)$, or simply AS when WF is clear from the context.

The foregoing discussion can be clarified by saying something more about the S/F-division. Of course, this distinction will have some arbitrariness. But it is plausible and helpful to assume that the S/F-division satisfies at least the following

S/F-splitting principle of minimal causality

(a) for all x and x', $OS(x) = OS(x')$ causally implies $OF(x) = OF(x')$,

(b) all elements of S are necessary to make (a) true in general.

We call x and x' structurally equivalent (or imitations) if $OS(x) = OS(x')$ and functionally equivalent (or substitutable) if $OF(x) = OF(x')$. Now (a) says that structural equivalence must causally imply functional equivalence. By consequence, there is a function associating with each set of structural properties a unique set of functional properties. The reverse implication is not required, functional equivalence does not imply structural equivalence, and hence there is no similar function. The reason for clause (b) is the following. Without (b), the splitting principle would allow S/F-divisions such that "S causally overdetermines F" and there is no reason for doing so. On the contrary, the larger F is, the more freedom in the choice of wanted and unwanted properties.

Note that we have not assumed that the splitting principle is sufficient for the determination of a unique division of RP in S and F. It leaves room for more than one possibility, the choice between them will be based on additional considerations. One further consideration may concern prices. It seems plausible to assume that the market price of a product is primarily determined by its functional properties, whereas the cost price is primarily determined by its structural properties. In other words, following the standard criticism of Marx' labour theory of value, it is assumed, and specified, that the cost price is determined by different aspects of the product than those which determine how much people want to pay for it. It may be useful to use such price considerations in the further determination of the S/F-division, for it is evident that cost and market price considerations play an important role in the R&D-process.

Let us now return to the intended and operational profiles. We noted already that as a rule the desired functional properties of the intended profile are provisionally decided upon earlier than the desired structural properties. For the operational profile of a prototype it may be the other way around. To some extent its structural properties will be known beforehand, and the question is what additional structural properties it has, and what functional properties.

In this way we have disentangled the two intuitions contained in the property/demand-terminology of Weeder c.s.: the distinction between factual and desired properties at the one side and between structural and functional properties at the other. The resulting asymmetric model will be called the S/F-model and is depicted in Figure 4, in which the arrow indicates causal determination.

It is plausible to assume that the comparison of prototypes in view of a fixed intended profile and of intended profiles in view of a fixed prototype is primarily a matter of comparing functional profiles. By consequence, it is also plausible to conceive the restrictions of the original definitions of the assessment notions of improvement and concession to functional properties as defining the basic assessment notions of the S/F-model. Hence, from now on we assume for the S/F-model, and for its extended versions in the two following sections, that "O" and "W" in Definitions 1 and 2 have been replaced by "OF" and "WF", respectively.

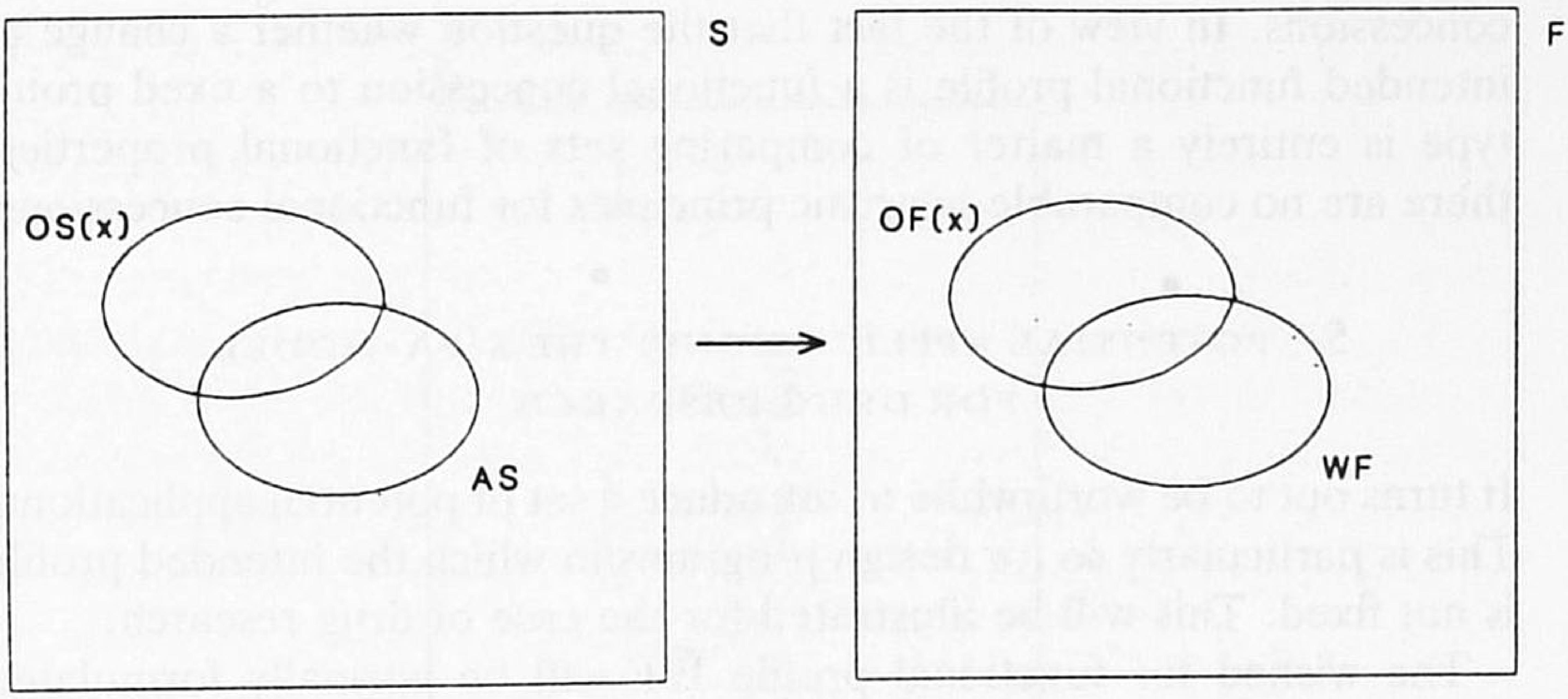

Fig. 4. A problem state in the S/F-model.

Moreover, it is now plausible to assume that preliminary estimations of judgements of functional improvements are suggested by ideas about possible relations between structural and functional similarity. It is easy to formulate some principles of which it is not only evident that they are formally *in*valid, but also that they play an important heuristic role. The basic idea is of course that structural similarity implies functional similarity, and vice versa. Restricting our attention to the qualitative cases we get the following heuristic principles, in which AS indicates an arbitrary appropriate structural profile for WF.

Heuristic principles

(HP1) if x_2 is structurally more similar to AS than x_1 (i.e., $OS(x_2)\,\Delta\, AS \subset OS(x_1)\,\Delta\, AS$) then x_2 will (probably) be a functional improvement of x_1 in view of WF (i.e., $OF(x_2)\,\Delta\, WF \subset OF(x_1)\,\Delta\, WF$).

(HP2) if x_2 is a functional improvement of x_1 in view of WF then x_2 will (probably) be structurally more similar to AS than x_1.

Intuitively speaking, (HP1) states that increasing similarity with an appropriate structural profile is likely to lead to increasing similarity with the intended functional profile, and (HP2) claims the converse. Because of the causal asymmetry (HP2) will have more exceptions than (HP1).

These heuristic principles concern functional improvements and not concessions. In view of the fact that the question whether a change of intended functional profile is a functional concession to a fixed prototype is entirely a matter of comparing sets of functional properties, there are no comparable heuristic principles for functional concessions.

5. POTENTIAL APPLICATIONS: THE S/FA-MODEL FOR DRUG RESEARCH

It turns out to be worthwhile to introduce a set of potential applications. This is particularly so for design programs in which the intended profile is not fixed. This will be illustrated for the case of drug research.

The wished for functional profile *WF* will be normally formulated with respect to a particular disease or to a range of diseases. For example, a therapy suitable for the treatment of angina pectoris, a particular form of ischemic heart disease, should affect the mechanical and electrical processes in the heart in such a way that the pathological condition of the patient will be restored.

Therefore it is useful to include a set of *potential* (*intended*) *applications* A, i.c. diseases, in the model. With the inclusion of this set results a model that deals with three types of profiles. It is called the *S/FA*-model. See Figure 5, in which $C(A)$ indicates the set of conceivable characteristics of potential applications, i.c. disease characteristics, while $C(y)$ denotes the profile of potential application y, i.c. the *disease profile* of disease y. Disease (and drug) profiles in which knowledge about diseases (and drugs) is stored, are extensively discussed in Vos (1991). Here, it suffices to state that disease profiles can indeed be considered as finite sets of disease characteristics.

The distinction between functional characteristics of drugs and disease characteristics is crucial. Functional characteristics characterize the biological responses of drugs whereas disease characteristics form the essential features of the pathological condition. In analogy to the splitting principle from Section 4 we can state that an application profile $C(y)$ uniquely determines the wished for functional profile $WF(y)$, but the reverse need not be the case. E.g. the reduction of the heart rate is desirable in the treatment of angina pectoris, but also in certain forms of cardiac dysrythm. The suggested *A/F*-splitting principle is, like the *S/F*-splitting principle, a causal principle in the sense that $WF(y)$ is causally necessary and sufficient to cure y, i.e., to free patients from the disease characteristics $C(y)$. Note that, whereas curing y is a matter

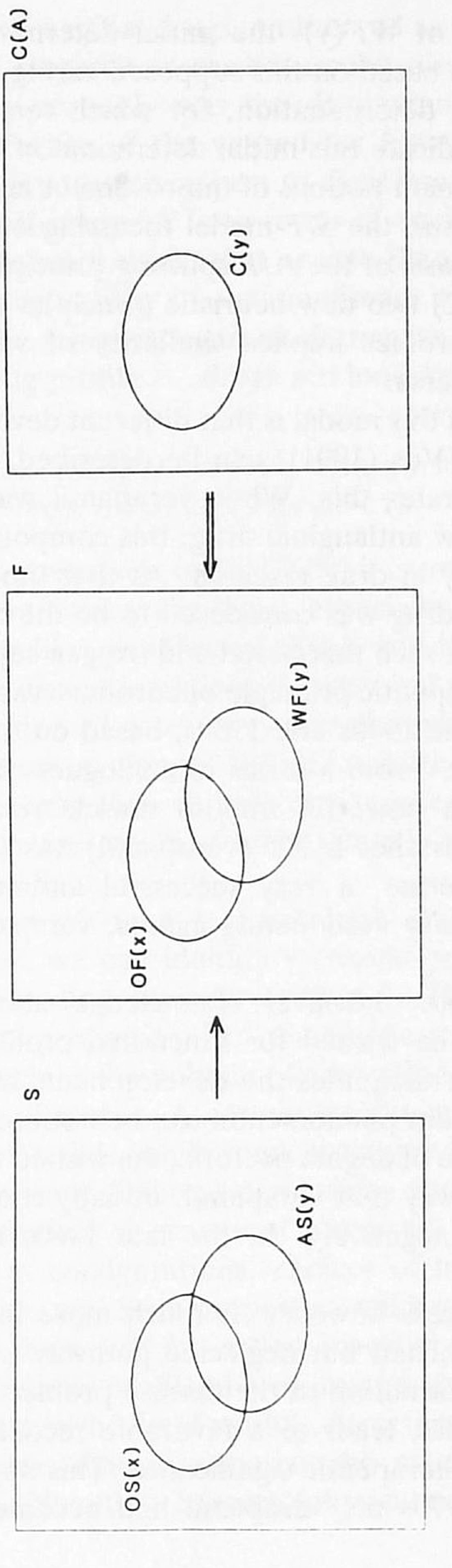

Fig. 5. A problem state in the S/FA-model.

of causal working of $WF(y)$, the initial determination of $WF(y)$ by $C(y)$, although it is based on this supposed curing effect, it is not itself a matter of causal determination, for which reason we have used a double arrow to indicate this initial determinaton in Figure 5.

The basic assessment notions of improvement and concession remain in the same way as in the *S/F*-model focussing on functional profiles. However, on the basis of the *A/F*-splitting principle we get in addition to (HP1) and (HP2) two new heuristic principles suggesting that similarity of disease profiles implies similarity of wished for functional profiles, and vice versa.

The advantage of this model is that different developmental pathways in drug discovery (Vos (1991)) can be described. The curious history of verapamil illustrates this. When verapamil was introduced in the early 1960s as a new antianginal drug, this compound was the result of a common pathway in drug research. At that time the desired action of any antianginal drug was considered to be the dilation of the blood vessels in the heart, such that blood and oxygen supply to the heart will increase. This therapeutic principle of coronary vasodilation dominated pharmacology of the 1940s and 1950s, based on then available knowledge of the disease. From a series of analogues of papaverine, widely acknowledged as a powerful smooth muscle relaxant and coronary vasodilator, the substance D 365 (verapamil) was selected. In comparison with nitroglycerine, a very successful antianginal drug and the prototype of coronary vasodilating agents, verapamil seemed to be a promising drug.

During the 1960s, however, knowledge about angina pectoris changed, whence the wished for functional profile changed. Though this description oversimplifies the developments in the field of angina pectoris, an important phenomenon can be noticed. Due to transitions in the disease profile of angina pectoris, the wished for functional profile changed in such a way that verapamil, initially considered a promising drug, was judged negatively. In the late 1960s it was considered a "dying drug".

The reverse process however, is much more interesting because it reveals a very important but neglected pathway of drug discovery. In this case the transformation of the disease profile, hence of the wished for functional profile, leads to a favorable reconsideration of a drug which had lost its therapeutic significance. This applies also to verapamil. During the 1970s the verapamil had become a prototype of an important class of anti-anginal drugs, and served as a tool in physiological and biochemical research on cardiovascular disease. One aspect of this complex history certainly was the distinction of two (sub)types of angina pectoris, hence of the wished for functional drug profiles. Verapamil was revaluated with respect to these profiles separately, and became a successful therapy for both forms of angina pectoris.

The history of verapamil shows that next to the common pathway of developing a new drug in view of a static disease profile, hence a fixed intended drug profile, a less-recognized alternative pathway exists, viz. given an existing drug profile . . . drugs are looking for diseases.

6. POTENTIAL REALIZATIONS; THE RS/FA-MODEL FOR COMPLEX PRODUCTS

As has been argued extensively in Sie (1989) it is sometimes also helpful to include a set of potential realizations, especially for design programs of complex products like complex machines and industrial production processes. Here the distinction between structural and functional properties and the inclusion of a set of potential applications, as outlined in the previous section, no longer suffice. A further refinement of the structural properties may then be helpful: the introduction of potential realizations *R* which are assumed to be directly related to the set of structural properties *S*.

For instance when we take a closer look at the development of aircraft technologies, we can identify technical properties like engine power, weight or loading capacity (volume). These may be distinguished as structural properties. But the engine power is a function of various variables such as the volume of the cylinders, the compression ratio and the type of motor. A certain weight may be realised using different kinds of materials, while some strictly required loading capacity leaves room for many different dimensions and geometries.

In fact, most technical or structural properties of products may be realized by different configurations, choices of material, dimensions, (chemical) structures, etc. Such properties will be called *material properties* and sets of them will be called material profiles or *potential realizations*. The *material profile* of a prototype gives a detailed specification of the product in the "real world". Structural properties are then properties or features that characterize the material profile in some more abstract way. Often they concern (physical or chemical) quantities expressed in their proper dimension. Another example is the operating pressure (or temperature) of some process line. These properties are characteristics which can be derived from the actual configuration (types and order of the machinery) and operation of the process.

Thus, once a potential realization is agreed upon, the corresponding structural properties are fixed. By consequence, we can state, in analogy to the splitting principle from Section 4, the *R/S*-splitting principle that material equivalence causally implies structural equivalence. The reverse implication, that structural equivalence implies material equivalence, is again not assumed. Of course, the *R/S*-splitting principle suggests heuristic principles in both directions: similarity of material profiles implies similarity of structural profiles, and vice versa.

When the concept of potential realizations is used in combination with the inclusion of potential applications, as described in the previous section, the result is a model that consists of four profiles. This model is called the *RS/FA*-model. Its basic assessment notions remain in the same way as in the *S/F*- and *S/FA*-model focussing on functional profiles. The core of the model is depicted in Figure 6, in which, in addition to Figure 5, $M(R)$ indicates the set of material properties of potential realizations, $M(x)$ the material profile of prototype x, and $AM(y)$ a material profile that is adequate for $AS(y)$.

The original sets of functional and structural properties are in this model refined by respectively the set of properties of potential applications $C(A)$, causally determining the corresponding intended functional profiles, and the set of material properties of potential realizations $M(R)$, causally determining the corresponding operational structural profiles. Hence, the *S/F*-splitting principle from Section 4 is enriched with similar splitting principles for the *R/S*- and *F/A*-interfaces and corresponding heuristic principles.

The *R/S*-division may even be such that the asymmetry between functional and structural profiles disappears, i.e., they may now causally imply one another. Functional properties like a "light" or "strong" aeroplane wing may be directly translatable into structural properties, such as the density of the material or the thickness of that wing.

The splitting up into four different profiles is especially useful when the product is very complex. For example, a full scale industrial production plant consists of many different parts. The design program that led to the development and construction of such a plant cannot be clearly expressed in terms of solely two or even three different profiles.

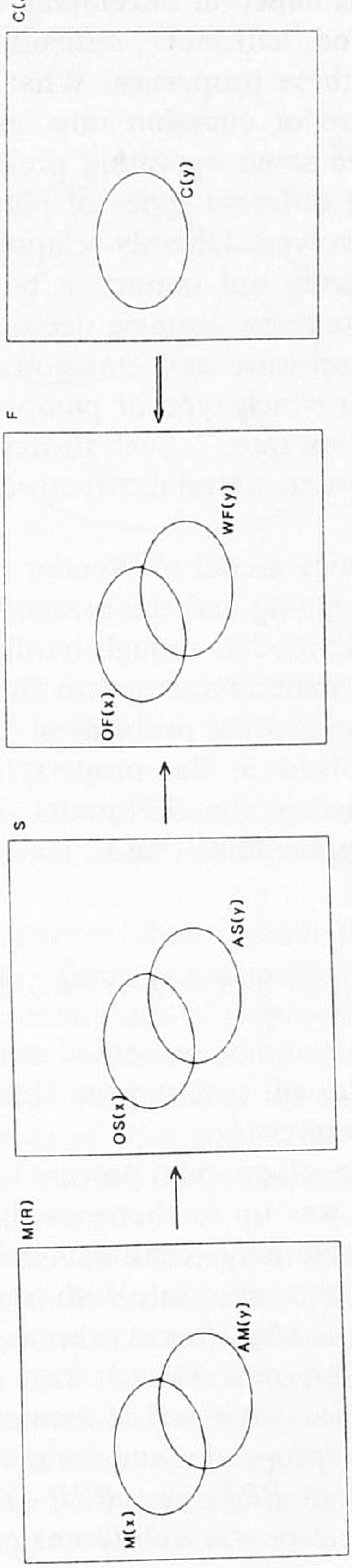

Fig. 6. A problem state in the RS/FA model.

When a design program is aimed at developing a plant with the functional properties "safe" and "efficient", difficulties may arise concerning the interpretation of these properties. What structural properties, such as operating pressure or emission rate, are required for these functional properties? The same operating pressure or emission rate may be reached by using different types of pumps, so that different material properties are involved. Directly relating the type of pump to its safety or efficiency leaves out important questions in the design program of the plant. Important strategic decisions concern questions like "At what operating pressure and emission rate is the plant safe and efficient?" and "With which type of pump do we reach that operating pressure and emission rate?". Such strategic questions explicitly assume the distinction between material, structural and functional properties.

Looking back at the lattice model of Weeder c.s. it is clear that the two ingredients of the foregoing and the present section were already essentially included in that model, though hardly with motivation, in terms of applications and materials, respectively. However, as we already argued, the main conceptual problem of that model concerned the mixed intuitions involved in the property/demand-terminology, which we have disentangled in the *S*/*F*-model. In addition, we have shown when and how "applications" and "materials" have to be included.

7. POTENTIALLY RELEVANT PROPERTIES

The foregoing refinements could be presented as a natural sequence of successive refinements. We will restart from the naive model to deal with potentially relevant properties.

At a certain stage in a developmental process it may be decided that a certain property, which was up to then not considered relevant, is relevant after all. The reverse may occasionally also occur: a property may no longer be considered as relevant. Both transitions make it clear that we have to consider a broader class of *potentially relevant properties* (*PRP*) as the domain of properties. At each stage there is then a subset of *PRP* of relevant properties composed of the non-overlapping sets *W* and *N*, the set of wished for properties and the set of undesired properties, respectively. The rest of *PRP*, i.e., $PRP-(W \cup N)$, *indicated by* *I*, is the set of, for the time being, indifferent properties. The oper-

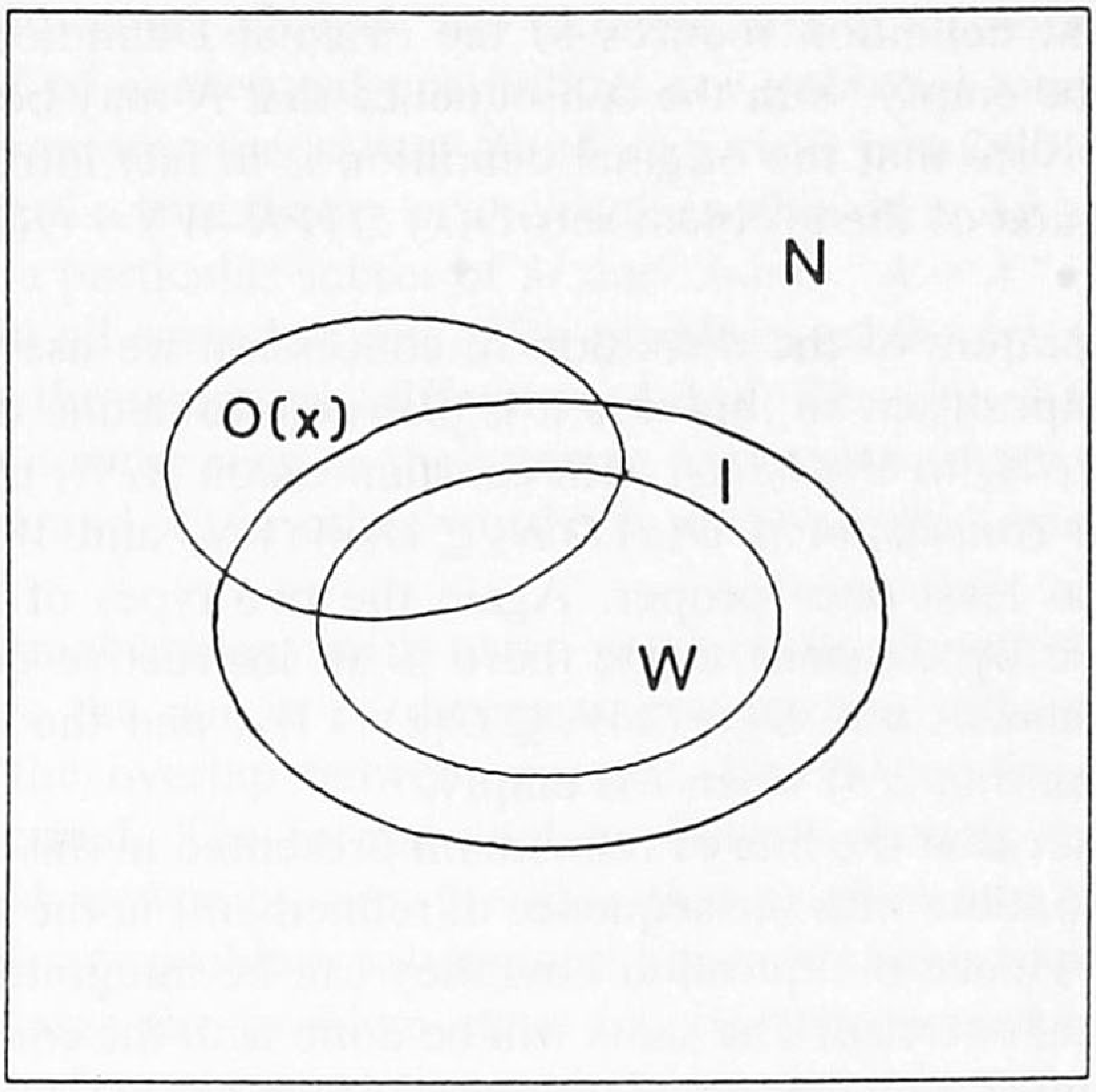

Fig. 7. A problem state with indifferent properties.

ational profile $O(x)$ is now of course the subset of properties in *PRP* which x actually possesses, and $PRP–O(x)$ contains the properties which x does not have.

I is the set of properties about which the different actors in the process may negotiate. There is not much to say about this in formal terms. However, the definitions of improvement and concession have to be adapted, where we will restrict ourselves to the qualitative cases.

To find the plausible adaptations let us start by noting that the problems in a given state of $O(x)$ and $W/I/N$-division essentially consist of two sets, $O(x) \cap N$ and $W–O(x)$, respectively. In Figure 7 the new problem situation is depicted.

Now it is plausible to call a transition from x_1 to x_2 in the face of a given $W/I/N$-division an *improvement* if the new sets of problems are subsets of the old sets, and at least once even a proper subset; formally, if $O(x_2) \cap N \subseteq O(x_1) \cap N$ and $W–O(x_2) \subseteq W–O(x_1)$, and at least once proper. We have already used the easy-to-check fact that the two types of problems cannot interfere, assuming constant $W/I/N$, for N and W do not overlap. It may be instructive to realize that the second clause is equivalent to: $O(x_1) \cap W \subseteq O(x_2) \cap W$. Finally, it is easy to check that the present definition reduces to the original Definition 1(a) by assuming I to be empty, with the consequence that N may be replaced by $(R)PR-W$. Note that the original definition is in fact introduced in terms of the union of the problem sets $O(x) \cap (PR-W) = O(x)-W$ and $W-O(x)$.

For the adaptation of the definition of concession we use the same problem decomposition. In this case it is plausible to define the transition from $W_1/I_1/N_1$ to $W_2/I_2/N_2$, with constant union RPR, in the face of a given x a *concession* if $O(x) \cap N_2 \subseteq O(x) \cap N_1$ and $W_2-O(x) \subseteq W_1-O(x)$ and at least once proper. Again the two types of problems cannot interfere by constant $O(x)$; there is an instructive equivalent of the second clause, viz. $O(x) \cap W_1 \subseteq O(x) \cap W_2$; and the definition reduces to Definition 2(a) when I is empty.

It is easy to see that the line of refinement presented in this section is essentially compatible with the sequence of refinements in the foregoing three sections. Hence the question how they can be integrated will be left as a technical exercise. The same will be done with the combination of the two technical refinements mentioned in Section 3 (R1) and (R2) and the others. By consequence, we may conclude to have partially presented and partially indicated a network of related models, with the naive model as point of departure and accounting for all six refinements mentioned in Section 3. Of course the choice of model for a particular case or class of cases will depend on the context.

8. RESEMBLANCE AND DIFFERENCES WITH TRUTH APPROXIMATION

There is an interesting resemblance between product development and truth approximation. This analogy applies already to the naive model which provided the simplest formal specification of the core idea of Weeder c.s.. According to the naive model, product development can be described as a process of trying to increase the overlap between two sets, the set of operational properties $O(x)$ of a prototype x and the set of wished for properties W.

In Kuipers (1982, 1992) it has been argued that the development of descriptive and theoretical (explanatory) research programs can also be described as a process of trying to increase the overlap between two sets. In particular, for the case of theoretical or theory-directed programs in the natural sciences it was argued that, from the so-called structuralist point of view, the ultimate aim is to characterize, within the set M of conceptual possibilities (or potential models) generated by the program, the subset X of empirical possibilities. This set X represents the true theory or *the truth* (within M). An arbitrary theory A selects a particular subset of M and claims "$A = X$". This claim will be false in all cases but one. The problems of theory A can be represented by the symmetric difference $A \Delta X$. The aim of theory development can now be seen as the attempt to decrease the symmetric difference of A and X, in other words, to increase the overlap between A and X.

The formal analogy with naive product development is obvious. In both cases the aim is to decrease a symmetric difference, that is to increase the overlap between to sets. But the analogy is more than merely formal. The formal analogy follows directly from a common conceptual viewpoint, viz. the idea that product and theory development both are problem solving and hence problem reducing activities. In both cases the problem state can be represented by a symmetric difference. It was in fact the conjecture of the formal and conceptual analogy of product development with theory development which suggested the naive model for product development.

So far for the resemblance. The differences, however, are at least as interesting and instructive.

(1) As long as M is fixed, X cannot be changed, whereas W can be changed, even if RP is fixed. The constancy of X follows directly from the assumption that nature does not fundamentally change in the sense that what is empirically possible and what not remains constant. That W may be changed is obvious. The degree of changeability, however, is limited as long as we keep the intended applications constant, but it is of course considerable if we change the intended applications.

(2) X is unknown, W is known. In theory-directed research, with fixed M, X can be considered as the great unknown where one is looking for. A fundamental complication is that one can never know to have reached this target (fallibilism). On the other hand, at every stage of product development it is known, at least in the naive model, which properties are wanted (constituting the set W) and which unwanted. That this division may change and that there may be indifferent properties for the time being, does not alter the fact that at each stage it is known on the basis of what division the operational profile has to be evaluated.

(3) A direct consequence of (2) is that it is impossible to evaluate in a direct way whether replacement of theory A by a new theory is a step in the direction of X. On the other hand, it can be judged directly whether a new prototype is an improvement "in the direction of W". Having the option of changing W, it is also possible to judge directly whether a change of W is a concession "in the direction of $O(x)$". Of course, we do not want to suggest that such evaluations are simple.

(4) In material respects it is relatively easy and inexpensive to change a theory. However, to change a prototype and hence its operational profile is usually a time and money consuming activity, similar to designing and performing test-experiments. In other words, changing theory A is essentially a paper-and-pencil-activity, which may of course nevertheless occasion much brain-racking. A change of prototype x (hence of $O(x)$) essentially requires material transformation.

(5) For fixed M, the A/X approximation process is, ideally speaking, free from external influences, the $O(x)/W$ approximation process certainly not. Given an explanatory research program, generating a fixed set of conceptual possibilities, theory development is something that can take place in the niche of that program. This is at least the case for the so-called internal phase of a program. In the application phase, theory development is directed to the solution of science-external problems or of problems raised by another research program. In the latter case, the first program functions as a supply program for the second, which plays the role of guide program (see Zandvoort (1986) for an illuminating analysis and case study). However, even in the application phase the cognitive factors influencing further theory development within the explanatory program are relatively easy to survey. On the other hand, from the network of models presented for design programs it is easy to see that there are many kinds of relatively external factors that influence the process of product development, making a survey in this case much more difficult.

In a number of these differences (1/2/5) the assumption that M is fixed is crucial. We would like to stress that in the initial phases of explanatory and descriptive research programs the conceptual possibilities are not only not fixed, but that they are even negotiable to a considerable extent, of course interwoven with the negotiation about what one is trying to explain or describe.

Despite the foregoing five differences, the resemblance is striking enough to show that theory and product development are both examples of problem solving activities which can be structured in such a way that the rationality of transitions from one problem state to the other can be defined in general and evaluated in particular cases.

9. THE SOCIAL CONSTRUCTION OF TECHNOLOGY

The presented network of models cannot only play a role in the description (and evaluation) of the development of products, it can also be used in the description of rise and fall of products that actually reach the market. Our primary claim is that the network of models is very useful for the first purpose. Vos (1991) gives an extensive illustration of this claim for drug research, in the present paper we could only give a glimpse.

However, Saviotti (1988), who introduced the distinction between structural and functional properties in the context of products reaching the market, and in particular Bijker (1990) strengthen our conjecture that the models are also usefulness for the second purpose. From Bijker's case studies concerning the bicycle, bakelite and fluorescent lighting, it becomes clear first of all that there cannot be made a sharp distinction between products which reach the market and those which do not. Moreover, in Bijker's approach the distinction between different groups of potential users of a product in the making turns out to be of crucial importance. In our approach this leads immediately to the recognition that these groups have different intended profiles. (Note that their sets of relevant properties will hence also differ as a rule; this can be easily accounted for in terms of Section 7: indifferent, potentially relevant properties.) Hence, our approach gains new perspectives from this conceptual link with Bijker's.

The same holds for Bijker's description of cases and his so-called "social-constructivist" theoretical analysis; both would have profited very much from this link, not in the least by demystifying some of Bijker's claims and notions. We like to conclude with some remarks in this respect.

According to Bijker (pp. 82–85) inherent "interpretative flexibility of artifacts" can be demonstrated by "deconstruction of an artifact into more than one artifact", each corresponding to a group. In our terms this pertains to nothing more nor less than the recognition that different groups may have different intended profiles and hence that in view of a certain artifact, with a certain operational profile, these groups are confronted with different problem situations. Thus, the same idea can be expressed less magical.

Also a number of technical terms of Bijker (pp. 92–97) can be explicated quite easily. His notion of "closure" essentially comes down to the phenomenon that the changing intended profiles of different groups gradually become more similar, which may or may not be due to the fact that one of them becomes dominant. Moreover, "stabilization" means that an operational and/or an intended profile becomes more and more clear. However, from our perspective it is surprising that Bijker does not introduce a third notion: "convergence" of an operational profile and an intended profile, due to successive improvements and concessions. Sometimes it seems as if he includes something of this into his notions of closure and stabilization. But from our point of view it is clear that these three types of development are to be distinguished conceptually.

NOTES

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