# Chapter 1

# What is a Process Model? Reflections on the epistemology of design process models

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## 1 Introduction

It is now established wisdom in the engineering design community that models are useful means of understanding and interacting with both products and processes. However this is a fairly recent development. A hundred years ago at the height of British engineering prowess, this was not the case. While it is possible that individual companies used informal models to describe their processes, formal prescriptive process models only emerged around World War Two and none of the current established process modelling techniques existed. After seventy years of experience, what can be expressed in process models, and how they can be used and interpreted, is still not fully understood. This paper describes some of the challenges that companies face in getting benefit out of process models and argues that some of them arise from the nature of models, as analysed by philosophers, and the nature of process models in particular.

Product models did exist. The earliest models of products had the same form as the larger thing to be created. As the complexity of the things made increased, product models became more abstract and selective. Engineers sketched, created schematic models of their products, and used graphical approaches to solve problems that are now solved numerically by a computer at the press of a button. Models serve many purposes in design, not just as visualisations of a product or process, aiding in idea generation, problem solving and evaluation, but also in facilitating the interaction of team members. How well a model can carry out these functions depends on the quality of the model.

However, assessing how closely a model describes its target (the object or process that it models) is far from simple. The relationship between a model and its target is fundamentally analogical, requiring the construction of a mapping between dissimilar things that have similar combinations of relationships between their parts (see Holyoak and Thagard, 1996). When the models are physical objects, the degree of abstraction required to see similarities between components and patterns of relationships isn't that great, but for mathematical and schematic models, making a connection between equations and diagrams and the form and behaviour of physical objects requires a much greater imaginative leap. But the relationship between a process model and a process is much trickier and elusive still, not least because process is itself an elusive concept.

Complexities arise from process models mixing ‘is like’ with ‘should be like’ (section 2), the subtleties of what exactly a model *means* (section 3), and conflicts in how models can be constructed and interpreted (section 4), as well as the wide variation in scope and detail afforded by different modelling approaches (section 5). We discuss the different roles models play in industry and the problems in building and using models we have observed in industrial practice in section 6, many of which are inherent in the nature of models; and relate our analysis of the conceptual complexities involved in process modelling to philosophical analyses of the role of models in science, a simpler problem that has attracted far more attention from philosophers than has design.

## 2 ‘Is’ versus ‘Should Be’

The term *process* is used in the design community to refer to two distinct but related concepts: (a) the sum of the actual activities that are or should be carried out to design a product or component or to solve a design problem; and (b) an abstract and relatively general conceptualization of what is done or should be done to design a product, that is meant to apply to a class of products, an organisation, or an industry sector. While many different kinds of models are used to describe the process in the sense of what designers actually do, processes as abstract conceptualizations are expressed in idealised and abstract models. For both meanings of process, what is being modelled by a process model can differ and be open to debate. For models of detailed behaviour, there are three questions, whether the model is an accurate description, whether it is understood correctly, and whether the process is the right process. For processes as abstractions, the question is whether the model is a correct or appropriate conceptualization for thinking about the structure of design activities.

Process models are employed for a number of distinct but interrelated purposes: to understand a process; to plan a process by determining what needs to be done when; to prescribe a procedure to be followed; and to predict how a process will behave, for example through simulations.

Process models divide, at first sight, into *descriptive* models – scholarly analyses of what happened in a process, or what happens in a category of processes – and *prescriptive* models – what designers *should* do to produce a particular type of product. For descriptive models, whether the model achieves its purpose is a question of whether it provides valid understanding. The relation between model and target has been extensively discussed by philosophers of science, but conformity depends essentially on the *accuracy* of the mapping between the structure of the model and the structure of the target. For prescriptive models, the relation between model and target is deontic, defining what designers should do: the model precedes its target, and reality conforms, or not, to the model.

This picture is complicated by models that capture best practice in frequently performed activities. These models attempt to describe how designing actually gets done, but only in selected or idealised cases, rather than as an accurate reflection of the range of behaviour in the category of activities they cover, and their purpose is to function as prescriptive models for future designing. Thus they have different conformity relationships to past and future processes, and the actual target of a description of best practice may not be clearly either an abstraction or an identifiable chunk of reality. In practice this distinction is blurred because in the attempt to generate descriptive models, one is confronted with a combination of descriptions of actual behaviour, as-is, and an account of what should have happened or should happen, as-should-have-been.

# 3 Philosophy of science perspective on models

The philosophers of science have thought very hard about what a model is and what it can represent, though the central importance of models in science was recognised remarkably late. Carnap (1938) famously remarked that 'the discovery of a model has no more than an aesthetic or didactic or at best heuristic value, but it is not at all essential for a successful application of the physical theory'. This is echoed in an even more dismissive view of high level abstract models in design by Lawson (1980), cited in Wynn and Clarkson (2005), that they are '…about as much help in navigating a designer through his task as a diagram showing how to walk would be to a one year old child...Knowing that design consists of analysis, synthesis and evaluation will no more enable you to design than knowing the movements of breaststroke will prevent you from sinking in a swimming pool'.

However, since the 1960s models have been placed at the heart of the philosophical understanding of science by construing theories as families of models (Suppe, 1989). Models have become recognised as a vital part of acquiring and organising scientific knowledge, because they represent the target in some form. Models are seen as isomorphic or similar to the target, whereby philosophers such as Suppe (1977) see a model essentially as a representation of the structure of its target. However Frigg (2003) explains representations in terms of three relations: denotation, display and designation: 'A model denotes its target system in roughly the same way in which a name denotes its bearer. At the same time it displays certain aspects, that is, it possesses these aspects and a user of the model thematises them. Finally, an aspect of the model designates an aspect of the target if the former stands for the latter and a specification of how exactly the two relate is provided'.

The representation comprises two mappings: an abstraction of real or imagined physical or social phenomena to a conceptualization of how they work, and an analogy between the structure of this conceptualization and the structure of the mathematics or objects and connectors that comprise the model itself. These abstract conceptualizations parameterize or strip out the contingent details of individual cases, such as exactly which parts are listed on a bill of materials, or safety margins of components, to define a category of possible situations sharing essential characteristics but free to vary in other ways. More abstract conceptualizations cover broader classes of superficially dissimilar things. This implies that abstraction is a process of selecting certain features and relationships as important and thereby discarding other features. Abstraction is driven by a particular purpose rather than being an absolute property of the range of cases it covers. This selection of significant features is biased by what seems to be important at a particular time from a particular viewpoint. Abstraction is often generalization over multiple similar objects or situations, whether concrete cases, idealized descriptions or skeletal memories, so that common features are selected to form the abstraction. Frigg (2003) argues that abstraction only exists if there is also one or a group of more concrete concepts that could provide a more specific description. A related dimension is the level of detail of a description or model.

Models in advanced sciences such as physics and biology are abstract objects constructed in conformity with appropriate general principles and specific conditions. Scientists use models to represent aspects of the world for various purposes, exploiting similarities between a model and that aspect of the world it is being used to represent, to predict and explain (Giere, 2004). Giere argued that models are not linguistic and do not have truth values; rather, that theories also comprise linguistic statements about the similarity relationships between model and reality, which do have truth values. However, while the mathematical models that are central to physics can be seen as clearly distinct from assertions about how they relate to the physical universe, separating the formal structure that makes a model a model from how it relates to its target is more problematic when the definition of the model takes the form of a linguistic description of its target. Nevertheless to constitute a model, the description defines an ideal type to which the targeted aspect of reality may or may not conform.

In the physical sciences, failure of a model to match observations is evidence for the inadequacy of a theory, though the conformity relationship is seldom seen as binary, and almost-successful theories are revised rather than abandoned (see Lakatos, 1970). Designing involves a complex interaction of cognitive and social phenomena. In the social sciences, models are more often conscious simplifications of complex situations that are partly dependent on contingent circumstances beyond the scope of the model, so the causal factors included in the model account for part of the similarities and differences between cases. Sometimes this can be quantified statistically in terms of the proportion of the variance in the values of the dependent variables that is accounted for by the independent variables included in the model. In these situations, it makes more sense to talk about how closely reality approximates to the model – degree of similarity.

However in design, process models are often prescriptive specifications, or are idealizations of best practice. Then the conformity relationship between a process and its model is rather more complex, because conformity is often not just a matter of 'is' or 'was', but includes deontic relationships: 'should' and 'must'. However, being accurate is not what a prescriptive model is there for, which primarily is enabling people to make inferences about how they should act to achieve a successful process. It might be more fruitful to speak in terms of appropriate models, that are fit for purpose, or inappropriate models, which fail to fulfil the requirements that are placed on them.

# 4 Interpreting models: a perspective from social science

Models are built for specific purposes by people, who select and represent the aspects of the process they consider to be important. They are understood and interpreted by different people according to their own goals, their own understanding of what they are doing and why they are doing it, and their own understanding of the social and organizational context they are working in. Each participant in a design process uses his or her distinct understanding of that process, informed by the models they use, as an information resource for guiding his or her actions. Process models serve as *boundary objects* (see Bucciarelli, 1994), whose labels for activities, types of information and communication channels convey information between specialists in different fields with different expertise, who see very different meaning in them.

The most well-developed and widely used approach to modifying and improving sociotechnical systems, *soft systems methodology* (Checkland, 1981), starts from the premise that the consequence of the subjectivity of individual understanding of social processes such as designing by the people participating in them is that they have *no* objectively true structure. Instead, any account such as a design process model constitutes one subjective viewpoint that isn't necessarily more true than someone else's contradictory view; any shared understanding is both partial and the outcome of a social process of negotiation. Hence, treating a social system as though it has an objectively true or correct structure is at best a pragmatically useful compromise – one that Checkland argued is misleading and should be avoided. We don't fully share Checkland's scepticism about as-if-objective descriptions of social structures and processes. But it is important to recognise that a very high degree of consensus about a skeleton of social facts does not imply a shared perception of their implications, and that alternative views of how processes work may be equally legitimate and valid accounts of how different people experience them.

Ethnographers have put forward the view that an ethnographic account of a social system is one possible valid partial truth among any number of true partial accounts, and the test of validity is that it looks right to the participants (see Hammersley and Atkinson, 1995). However for process models, it is not enough that the model looks right to all the people involved in generating it. It must also be useful to those who just pick it up. It must enable its users to make valid and valuable inferences about how the process behaves and how they should act.

Design process models are interpreted by their users – and how they are interpreted by the participants in the process can be significant for how designing happens. Design process models are interpreted differently by different people in two ways. First, people differ according to their perspectives, knowledge and experience in the range of possible concrete situations and actions they can imagine as possible, or regard as feasible or appropriate, hence in what range of possible processes they see a model as encompassing. Disagreements may stem from mismatches in assumptions rather from consciously articulated beliefs. Second, people differ in how they interpret the epistemological status of the model, as mandatory specification of actions, or of goals to be achieved, or as guidelines to be used or adapted as each new situation demands.

## 5 Models vary in scope and detail

Rather than reviewing different modelling approaches, this section reflects on the categories of models and some of the conceptual challenges of modelling design processes. Wynn and Clarkson (2005) review generic process models; and Browning and Ramasesh (2007) review modelling techniques for specific proceses. Regardless of the type of model used, models are affected by the following factors:

**Selection**: Any model is a form of abstraction, as it requires people to select what they consider to be significant. This selection applies both to the features which are included and to the scope of the model. For example many process models do not explicitly include the documentation that designers produce, as they don't consider it a design activity; nevertheless it is a vital part of any design process, especially for certification.

**Representational bias: T**he type of process model determines what can be described in the model and therefore biases the selection of elements that are included in a model. For example stage gate processes do not include iteration (although in practice, failed stage gate reviews sometimes need to be repeated, so iteration can happen at that level of abstraction). Flowcharts make iterations explicit, but do not indicate location in time.

**Modelling choices:** Even within one representation formalism, the choices of the modeller determine what properties the model displays. For example if there is frequent iteration between two tasks, they can be shown as two tasks and an iteration loop or as just one task, in which case the iteration would be buried. If this iteration later causes problems, the simpler model would have hidden the behaviour, and therefore would not have been fit for purpose.

In many design domains models can be developed or proposed based on observations of multiple instances of similar phenomena. There are practical limitations to the number of cases and level of detail it is possible to look at. For example Eckert (2006) could look at multiple knitwear design processes, because they are short and quite simple, compared to engineering processes, like aircraft design, which require millions of person hours. While it is impossible to compare large-scale processes in their entirety, it is of course possible to look at tasks that are performed in a similar fashion in many processes. Therefore it is possible to have a set of generic models of limited scope, e.g. of stress analysis of certain components, but it is rather more difficult to produce a model of the process of, say, an entire jet engine. The variation between projects lies in the way these various repeatable processes are combined. Few people have the required overview to see similarity across multiple projects (see Flanagan *et al*, 2007).

Detailed models describe repeatable activities and are quite easy to produce, e.g. how to do stress analysis. High level models of the entire process in terms of a few selected core activities also remain fairly constant, e.g. each car requires styling, design of the engine and power train, design of the interior etc. Very large organisations can have a cascade of models – broad-brush stage gate processes for the whole company, and more detailed adaptation of these processes for local conditions and products that are required to conform to the models enshrining company policy.

The difficult modelling problem is the middle ground of models with a broad scope and a meaningful level of detail. Connectivity models such as design structure matrices (DSMs) try to capture dependencies between the elements of a model, but are notoriously difficult to build. Specific process models for process planning are therefore a special and difficult case. Not only can they not be based on multiple instances, they cannot be based on any instances at all that they actually apply to. They are the result of the application of abstract knowledge and reasoning by analogy from past experience.

# 6 Process modelling in industrial practice

The empirical insights reported here are based on various case studies that were concerned with modelling and planning design processes in complex engineering domains.

In 2000 an empirical study was carried out in an automotive company to understand the range of models that designers used to plan design processes. Over a period of six weeks 18 experts were interviewed in one company on two sites, including engineers, engineering managers and business managers. This revealed many of the divergent views on models and applications for models (see Eckert and Clarkson, in press). In 2004 to 2005 we were also involved in studies of processes in another automotive sector company, which had worked hard on introducing Six Sigma and other prescriptive approaches across the organisation (see Flanagan, 2006).

The most recent process modelling activity we were involved in took place from 2005 to 2008 in an aerospace company where the early conceptual design process was modelled in P3 with the view of developing a new process for conceptual design (Eckert *et al.* 2008).

All studies consisted of a combination of interviews, which were recorded and largely transcribed and informal conversations with designers and design managers. Many of the attitudes reflected here emerged as throwaway comments during interviews and were then taken up in informal conversations with design managers.

## 6.1 Models serving as process plans

Rather than just employing process models to plan design processes, designers and design managers make use of different models for product, process and quality. Product models such as cost models or bills of materials are used to track progress through the process. Process models are generated – often informally – by individuals and teams, and on a formal level for the entire project drawing both on activities and prescribed stage gates. However as different parts of a design don't evolve at the same rate, lead time plans and test schedules are developed at a component level. To cope with emerging crises teams often develop fire fighting schedules, which deal with one issue to the exclusion of others, thus often propagating the problem. Eckert and Clarkson (in press) found that rather than have an explicit procedure to co-ordinate these different models and resolve conflicts between them, key stakeholders interact with more than one plan and bring these together as and when required.

Single integrated models are unlikely to exist; projects are modelled in a combination of different models. How these models relate to each other is often not made explicit. For example, for a flowchart style model, individual tasks are often broken down into further flowcharts. For the lower level models to make sense in their own right they need to repeat elements of the higher level models, without clearly indicating this. This duplication issue is most critical for time buffers, where everybody would like to add their own buffers, but not everybody needs to add buffers for the same iterations or unexpected tasks.

In the case study companies designers or design managers were given little advice on how to generate their process models or explicit instructions on what to include. While it is relatively obvious what needs to be in a product model, it is less clear what needs to be included in an activity plan, either the level of detail required or the type of activities that are included. Therefore the responsible people based their plans on what they were familiar with, not just in the style of the plans, but also in content. The engine company had developed a sequence of similar products by incremental improvement, and had a number of very experienced engineers who were able to mediate between different teams (see Flanagan et al. 2007), so had the knowledge needed to develop process plans. The situation was more challenging in the car company, which tried to design a new car with a largely newly assembled team at a second site. As many people had recently joined the organisation, they developed models of very different styles and content, based on the models they had seen in their old teams.

## 6.2 Challenges with building models in industry

All these models are partial in two ways: (a) By the way they are constructed they focus on particular aspects of the process, such as the sequence and flow of documents, or testing schedules. Being focused is an inevitable property of models. (b) They are also limited in their scope. Both automotive companies had systematic integrated product models, such as bills of materials, which also had a process function, but the process models only covered parts of the process.

The product and the process constrain each other. If process models are generated before the process has unfolded, the models are based on a prediction of what the product will look like and therefore what process it requires. If the process is determined in advance, it limits the range of possibilities for the product.

Typically the engineers try to relate what they know they have to do to what they had done previously on other projects, and reason by analogy to adjust the process that they know accordingly. If they think it will require significant new work, they might add more time to individual tasks and add tasks for validation. If the design is expected to be routine, they might reduce the expected time. As everybody has different experiences process models therefore are to some extent subjective in the way they are constructed.

Process models are also affected by the personality of the person who builds it. While some people are very cautious and base their process models on the worst case scenario, others are optimistic and provide models based on an ideal path. This is most pertinent in time estimates, but can also affect the structure of a model. It is not possible to see from the model itself whether an estimate is based on the best case, the worst case, the most typical case, or the most recent case. Even if directives were given for that or the creators of models would offer an explanation, this could not be taken for granted.

Organisational culture can discourage accurate planning or modelling of processes. If the way people book their hours is ill-aligned to the plans that they generate, then the record of the process will be a mismatch with the plan for the project, just because people needed to book time against the tasks of the particular project they mainly work on. Providing accurate plans for processes is often not rewarded in organisations, who praise people for process plans that are ambitious, rather than plausible. If over-ambitious plans fail, the people are often rewarded again for finding a way to rescue the situation. This nurtures a fire fighting culture, whereby teams concentrate on sorting out individual problems, often to the detriment of other tasks going in parallel.

## 6.3 Attitudes to processes and process models

This section reflects about the attitudes to process models that engineers convey in the interviews we have conducted. This is an interpretation of throwaway comments of interviewees and complaints of project managers. However, in discussions with senior engineering managers, these observations rang true to them.

While it is possible to identify some of the ways in which models are wrong, by being incomplete, defining impossible or implausible task sequences, or making statements that are factually wrong, it is inherently difficult to say whether a model was “right” or “fit for purpose”. People talked about “right” and “wrong” process models in very similar terms to product models, where comparisons can often be made between product and model. This lack of reflection about what a model can provide lies at the heart of the attitudes to process models discussed here.

The way models are constructed and their inherent properties make it very difficult to interpret how good a model is and what it can give people. None of the engineers we discussed models with are much aware of the practical and conceptual difficulties of creating, using and introducing models. They did not comment on the inherent limitations of modelling and seemed not to be aware of the practical limitations of models. They also showed no awareness that other people might interpret the models in a very different way. They assumed that their understanding of the model was “the” sensible interpretation and therefore assumed others would reach it as well.

However the resulting interpretations were very different. Some people saw process models as “schedules” that they could follow and needed to follow. Like a “timetable” showing the sequence of stations, the plan shows the sequence of activities. If things don’t work out, they are disappointed by the people who carry out the process. The other end of the spectrum are people who see processes and process models as vague indications of what they might have to do, rather than anything binding, because they sense that something that is that “wrong” cannot be prescriptive.

People sometimes dismiss process models if some aspects of them are wrong, such as duration or order of tasks, rather than recognise that the models could still be useful if some of the information is wrong or no longer relevant, in the same way that a train timetable is still useful when the train is late, because it shows the route the train travels and the journey time on the plan is at least the minimum it can take.

Process champions, that is, people who really push a particular process, model or modelling approach, are very important in an organisation. Without them introducing a process is very difficult and people would not provide models of their individual activities. However, too much zeal can be very offputting. If the champion pushes too hard people believe that rather than supporting them in successfully bringing the project to a conclusion, they are only interested in making sure their model is adopted. They end up following a process because they have to rather than because they see merit in it.

# 7 Conclusions: Applying process models

This paper has argued that in practice creating, handling and using process models in still problematic. While engineering activities are recurrent at the level of local tasks, where the procedures can be modelled based on multiple projects involving the same activity, and involve the same key tasks and major phases at a high level, they are very difficult to model at a medium level of abstraction, where people do not have the required overview and cannot draw on experiences with multiple similar products, because the specifics of projects were different.

Some of the problems are caused by management issues. However, many problems arise from the nature of models themselves. Many designers and managers do not understand what information a process model can provide them with and think of them in a similar way to product models.

It is important to recognise the properties of process models in managing and directing a process, because process models constrain and shape the processes to which they are applied, through the same aspects that make them useful. They provide information about the structure, dependency and preferred order of the activities and often contain rich additional information in terms of resources, constraints, times and so on.

A process model does not need to be totally correct in order to be useful, nor does correctness guarrantee usefulness. The coarser the models, the more likely they are to be correct, but the less assistance they provide. A model that is wrong in some respects can be useful, as long as the users understand what the model can provide.

Using models to understand, develop and follow design processes can be problematic and lead to confusion and misunderstanding at four levels. First, a process might simply be misunderstood, or a prescriptive process might be an inappropriate way to achieve its intended result. Second, a process may be conceptualised, validly, in different ways according to the perspectives and priorities of different people. Third, as modelling involves prioritisation and selection, a shared understanding of a process may be modelled in different ways. Fourth, a model is interpreted by its different users according to their own experiences, knowledge and concerns, which may include conflicting unarticulated assumptions. All of these are significant issues in industrial practice.

Process models are built by individuals based on their own experiences for a particular purpose, which is usually not stated explicitly. Modelling inherently involves selecting some aspects and excluding others. One could argue that process models are always wrong because models exclude factors which might become important, because of the fact that they are excluded from the model. A process model draws the attention of the user to particular aspects of the process, tempting them to ignore others. If a model shows up potential problems, such as resource shortages in critical areas or the lack of interaction between important tasks, this encourages people to try to fix these problems, so that the problems go away. In a prevailing fire fighting culture this is likely to open up a gap somewhere else.

Rather than being a depiction or a set of instructions a process model can be thought of as a self-fulfilling prophecy. A prescriptive process model, or, more subtly, any model used to derive process information during designing, makes the process behave in the way it describes, because it is used to manage and understand the process for which it exists. Models here set goals and people are assessed against them. However they also provide a context in which isolated tasks or activities are carried out, and therefore shape these activities towards the expectations they generate about the rest of the process. Descriptive process models can also exert an influence on behaviour, because as they become the record of what has been, they influence the memory of the participants, and influence other people's understanding of how to design. As process models are inherently open to different interpretations, these interpretations of what the structure of the process is and how it is meant to guide behaviour influences what the process turns out to be. These interpretations may be in conflict.

It is important that designers and managers understand that models can be interpreted in different ways and that people have different expectations of them. Rather than prescribing an interpretation of models, the understanding of the role that models can play in an organisation needs to be negotiated within a team and an organisation. An understanding of a model is a cognitive construct rather than an inherent property of the model, and a shared understanding is constructed through social processes of discussion and clarification.

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