

Reflections on artifact related process modeling

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Abstract

In this non-exhaustive inventory, process modeling techniques are analyzed with regard to their potential for integration with artifact modeling techniques. This is done based on a classification, distinguishing (a) temporal, (b) structural, (c) logical, (d) functional and (e) behavioral process models. The potential for inclusion of artifacts is judged based on the possibility to incorporate (1) artifact knowledge on different levels of artifact complexity, (2) qualitative and quantitative artifact knowledge, and (3) the availability of smooth transitions from and into artifact models.

Based on these criteria, none of the process modeling techniques reviewed offers full potential for artifact integration. Dynamical Finite Element Modeling is the most successful attempt encountered so far, but it has its shortcomings as well. Further work is needed to complete the overview and to devise an effective strategy for integration.

Keywords

Process modeling, artifact modeling, integrated models, knowledge inclusion, computer-aided design.

1 Introduction

During conceptual product design, there is a close interaction between the artifact being modeled and artifact related processes. Sometimes the consideration of an anticipated process precedes the origination of the artifact, e.g. when the way it should operate is given. In other cases an artifact related process is derived from the artifact description, e.g. to investigate how it behaves, or a process is developed based on an artifact description that was created first, as is sometimes the case with manufacturing processes.

The ultimate goal of the research behind this paper is to realize a computer supported integral artifact-process modeling method that provides a smooth transition between process modeling and artifact modeling in both directions, allowing for preserving both the process-related knowledge and the artifact-related knowledge. In the case of the current approaches it is sometimes possible to reason from a partial artifact representation about a partial process representation or vice versa. Nevertheless, no computer supported mechanism is known that preserves the knowledge 'from the other side' once a transition has been made.

A lot of books, papers and articles can be found in which the various models for artifacts have been reviewed in order to describe the state of the art in this field, and also to present what has been done to integrate the various artifact models (Shah, J.J. and Mäntylä, M., 1995). Process models have also been reviewed for various purposes, e.g. for design process modeling (Smith, R.P. and Morrow, J.A., 1999). It can already be stated that by this time, there has been large number of process modeling techniques available. Although there have also been certain attempts to integrate process related aspects and artifact related aspects into one modeling technique, so far no exhaustive review of process modeling techniques has been done from the perspective of integration with artifact modeling. In this paper, which can be regarded as a first move towards such a review, some process modeling techniques are analyzed from this point of view. Based on a non-exhaustive literature search, a bird's eye overview is given in which some of the integration attempts that have been made so far are explored and classified.

This paper is structured as follows. Section 2 suggests a classification scheme for process models and section 3 discusses key characteristics for the potential of artifact inclusion. In section 4, process models belonging to each class in their purest possible forms are reviewed. Section 5 deals with the more complex process models generated as various combinations of the basic classes. Section 6 discusses further generalizations based on the inventory, and it highlights questions and issues related to further integration of artifact and process modeling. Section 7 concludes with suggestions for further steps towards a methodology for inclusion of life cycle processes in product modeling.

2 A classification of process models

Preceding the brief review of process models, it is specified what a process model is according to the understanding of the author. Pending a more rigorous set of formal definitions, a process is defined as ‘a change in something during a period of time’, in accordance with Hubka, V. and Eder, W.E. (1988) and others. Models of processes are made for two reasons: (1) as an abstraction to simplify a real (existing) process as it can be observed, and (2) to structure and formalize a — nonexistent or not yet existing — imaginary process.

The process models in this brief inventory have been collected by performing a literature search and including models that were explicitly discussed as process models. The paper also includes representations that have not been intended to be process models in the first place, but nevertheless can be regarded as such. Also included are some familiar process models for which only secondary references — or no reference at all — could be found in literature. For some very commonly known process models, the benefits of finding a relevant literature reference would not weigh up against the effort needed.

In the process models that will be discussed here, the ‘something’ that changes in the process can be an artifact, a system of artifacts, a person, a system of persons (e.g. an organization), information or any combination of these. In product development and in mechanical engineering, artifacts and artifact systems usually play a central role. For this paper, however, other ‘somethings’ have not been a-priori excluded.

In order to structure the review of process models, a classification referring to what they represent or contain is put forward. Five categories were distinguished, but it is not claimed that this classification is exhaustive, or that it is the best possible or the most useful one. To express the key issues of the categorization, the descriptions below refer to process models adhering to one category exclusively:

1) temporal models.

In addition to representing identifiers for the sub-processes, purely temporal process models only include information about starting times, finishing times and/or durations of process components.

2) structural models.

Structural process models represent information about the structure of a process only, i.e. how the elements of a process are arranged with respect to each other. This can be an arrangement in time and/or place (for purely structural models: without quantitative reference).

3) logical models.

Logical process models address the logical dependencies between the process elements, i.e. the conditions that determine whether elements in a process exclude or allow each others execution.

4) functional models.

Functional process models represent the potential functions of the elements in a process, i.e. the purpose the process elements are considered to serve. Functions are usually expressed by a verb-noun combination or some extension of this type of expression in natural language.

5) behavioral models.

Behavioral models represent the scientifically verifiable characteristics of a process. If we make the simplification of excluding human and social behavior (as is usual in engineering), these representations are typically based on a quantitative process description built up from parameters, variables, constraints etc.

This classification is used to structure the reviews on the highest level; for structuring on a lower level, the inclusion of artifacts is used, as described in the next section.

3 Artifact related aspects in process models

To structure the treatment of artifact related aspects, two key characteristics of artifact inclusion will be discussed: (a) complexity and (b) exactness. Both address artifact knowledge issues.

Ad (a). Artifacts can be represented at a compound level, e.g. assembly level in which various components appear, or at a detailed level, e.g. related to the description of a single part’s geometry. This characteristic corresponds to the way an artifact can be decomposed. The process model may also include knowledge about this decomposition.

Ad (b). Artifact representations can range from a qualitative notion to a quantitative specification. This notion or specification can apply to various properties of an artifact: its identification (e.g. its name or its ordering number), its metric appearance, its weight etc. A higher degree of quantification can indicate that more knowledge about the artifact is included. However, artifact related numbers do not always represent a high content of artifact knowledge in the process model. They only do so if they are already explicitly included in the process model for the reason that (1) they also have a process related meaning or (2) the process model is already intended to include artifacts.

4 Process models restricted to one category

In the subsections 4.1 through 4.5, a first exploration regarding the potential for inclusion of artifact related aspects in process models is carried out. The review is confined to existing process models and existing modifications of such models.

In order to mark the distinction between the five categories of process models, the most basic representatives will be addressed first: it is attempted to identify process models that are restricted to one category only. Next, in section 5, those process models will be addressed to which one category applies in a concrete way and one or more other categories are included either on a secondary level, or hidden, or implicitly. The potential for artifact inclusion will be discussed based on the two key characteristics and the knowledge issues mentioned in the previous section.

In those cases where models have a highly artifact related content, the potential of supporting transitions between artifact representations and process representations will be addressed as well.

4.1 Temporal process models

An example of a strictly temporal process model is the familiar Gantt chart in its simplest form, as it is used for scheduling tasks in projects. Also, the original version of PERT (Program Evaluation and Review Technique) from 1958 is often said to exclusively represent time aspects. Nowadays, PERT can only be found in extensions such as PERT/CPM, GERT and Q-GERT, e.g. Smith, R.P. and Morrow, J.A. (1999), which include notions of structure and behavior.

The only mechanism that can be used to include artifacts in purely temporal process models is by referring to them in the names of process elements. For instance, if a Gantt chart represents a milling process, an element may be called 'mill pocket'; if it represents an assembly process, one of its elements may be called 'gearbox'. The complexity of the artifact description in this case is arbitrary. It can range from detailed, e.g. addressing a geometrical feature ('pocket'), to compound, e.g. addressing an assembly ('gearbox'), but in this respect the process model does not reflect any knowledge of the artifact's decomposition.

The artifact representation is qualitative rather than quantitative. It is possible to include artifact related numbers in the names, but they would have no meaning in the existing process model.

4.2 Structural process models

Examples of purely structural models are Kusiak's Process Graph and Process Tree (Kusiak, A., 1994) (note that the term 'Process tree' is also used for other representations), and other tree-like representations like the assembly tree or assembly fishbone, e.g. Beiter, K.A. et al. (2000). The tree representations impose a structure over the time space, reflecting our semantics without explicitly addressing time. The structure displays a decomposition and a sequence of process elements in time.

Artifacts can be included in these process models by naming them in the identifiers of process elements. The decomposition of process elements may correspond to the decomposition of an artifact, as is the case in the assembly tree, so in this respect there is a potential to include some artifact knowledge. The complexity is arbitrary — for instance, an assembly tree can be made on assembly level only, if it just contains the major sub-assemblies of a system, but it is also possible to extend it with manufacturing instructions for details on part level.

There is little potential for including quantitative knowledge, but it is possible to attach an artifact related meaning to, for instance, the repeat count of process elements that also correspond to the quantity of identical parts needed — or to part numbers (e.g. 'insert screw no. 6651/A, 4 times').

4.3 Logical process models

The AIDA (Analysis of Interconnected Decision Areas) formalism is an example of a purely logical process model, exclusively representing the mutual compatibility of candidate process elements (Harary et al., 1965). This model offers little potential for artifact inclusion. Like in a Gantt chart, names of process elements can refer to artifacts or they can contain numbers that relate to artifacts, but artifact related aspects are not explicitly treated in the process model.

Also focusing on logical aspects is the state transition model and other similar techniques used for representing the subsequent states of machines, mechanisms etc. usually performing a cyclic process. This type of models shows the conditions for the execution of steps in the cycle, as previous and parallel steps determine them. This can be done with explicit reference to time, but a reference to 'steps' alone is often considered sufficient.

This type of process models can include references to states that artifacts can assume, which potentially includes all properties that change in a process. Theoretically, even constant states can be included, but doing so would stretch the original intent of the model. The model can apply to artifacts at both a high and a low complexity, and the states covered in the model can be represented both in a qualitative and a quantitative way.

4.4 Functional process models

A functional process model in its purest form is the 'Gesamtfunktion' or overall function as it is defined in Koller's design methodology (Koller, R., 1976). The 'Gesamtfunktion' embodies the functionality of an artifact system purely intended for performing a transformation process, in a verb-noun-based expression. Furthermore, it includes a description of the input and the output of the process. The overall function is a very condensed process model consisting of only one element. The methodology covers further decomposition of the overall function as well, introducing structural and logical aspects as described for the functional models in subsection 5.4.

Although the overall function represents an artifact system, its high complexity indicates that it has to be regarded as a process model rather than an artifact model, more so because the artifact does not yet exist. The hcomplexity also implies that it represents the artifact on main assembly level. Quantitative information about this artifact cannot be included, since the artifact is supposed to be nonexistent.

If the eventual artifact system is devised to transform other artifacts, representations of these artifacts may be included in the input and output specification. This topic is addressed more profoundly in section 5.2.

4.5 Behavioral process models

The literature search did not yield any purely behavioral process models. Even the most basic behavioral process models still explicitly include time; therefore they are always temporal as well. Nevertheless, in this subsection those models will be discussed that are behavioral and temporal, but which do not belong in other categories.

Although it might seem trivial, time dependent mathematical *equations* can be considered the most elementary behavioral-temporal process models, whenever they describe process changes. Equations can appear in various forms with diverse complexity, e.g. differential equation, integral equation, matrix equation etc. By solving the equation one can obtain an objective description of behavior, expressed as the course of other variables as a function of time. Most equations originally stem from analytical attempts to describe and explain physical phenomena in existing systems. In engineering, the same equations or derived equations are used to predict the behavior of systems before they exist. It is not always possible to solve equations analytically, so it is not surprising that since the introduction of the computer, numerical methods for solving various kinds of equations have become increasingly popular. Some examples of complex behavior prediction using numerical techniques can be found in Baraff, D. (1994) and Horváth I. and Kuczogi, G. (1997).

In equations, artifacts are usually represented in two ways. One is the inclusion of the name of an artifact in a variable and the other is in the values of known variables, as far as they represent artifact properties.

In this case, the complexity of the artifact description can range from detailed (e.g. if all the variables relate to features of a geometry) to compound (if the variables relate to several components).

It is obvious that the artifact representation is quantitative if the variables are quantified. But it is also possible to reason with equations in a more indistinct way by not quantifying the variables (symbolic manipulation), or to superimpose statistical distributions on variables.

A group of behavioral process models closely related to the equation is that of time-related graphs, time-related listings with variable values etc., which are often created as the output of equations — or other behavioral models, as we will see. A typical characteristic of this type of models is its low knowledge content: the reasoning (e.g. the equation) on which the graph or listing is based, is not included.

5 Process models covering more than one category

Many process models do not exclusively represent temporal, structural, logical, functional or behavioral properties of processes. But most of these process models emphasize one of the aspects, usually according to the purpose for which the model is intended. For instance: many models represent a structure, but some of them primarily serve to predict behavior, whereas others, for instance, are primarily intended for reasoning about functionality.

In the following paragraphs, the combined process models will be discussed according to their emphasis: primarily temporal, primarily structural etc, and for each model, the aspects that are covered beside this focus, including artifact aspects, are considered.

5.1 Primarily temporal process models

Process models in this category usually serve to optimize the lead-time for a planned — or prescribed — process, and most of them apply to project management. For this, they also include structural aspects — for instance CPM (Critical Path Method) and the WTM (Work Transformation Matrix) (Smith, R.P. and Morrow, J.A., 1999). In addition to decision support for finding the optimal arrangement of process elements, some extensions of these models also offer predictive capabilities, like GERT (Graphical Evaluation and Review Technique), Q-GERT (Smith R.P. and Morrow, J.A., 1999) and signal flow graphs (Nukala M.V. et al. 1995). One of the most important issues for such models is to predict the most probable lead time for the optimal process arrangement, taking into consideration various kinds of disturbances, sometimes with a stochastic character, like waiting times, iterations etc. Such extensions also add behavioral features to the process models.

This type of model offers little potential for artifact inclusion. Like in a Gantt chart, names of process elements can refer to artifacts or they can contain numbers that relate to artifacts, but artifact related aspects are not explicitly treated in the process model.

5.2 Primarily structural process models

In this category we mainly find process models for structuring the components of organizations, information systems and manufacturing systems to make them suitable for carrying out a required overall transformation process. The DFD (Data Flow Diagram) is a structural process model that also includes references to the functionality of the elements (Yourdon, E., 1989). IDEF0 and IDEF3 are other well-known combinations of structural and functional process modeling; IDEF3 also includes logical relationships between process elements (Kusiak et al., 1994). For IDEF3, even simulation capabilities have been claimed but not yet realized (Padmanaban, N. et al., 1995), addressing behavioral aspects in the model.

Typical items in this category of process models include input and output for the process elements and flow direction for the matter, energy or data to be transformed in the process.

This type of process models offers more potential for artifact inclusion than the purely structural models discussed in section 4.2. Rather than just by being mentioned in the identifiers of the sub-processes, artifacts can be represented by the structural elements that connect the sub-processes, for instance by input and output arrows. Such representations are qualitative and compound: the process models are not sufficiently specific in that they can handle detailed and quantitative artifact relation in a meaningful way.

In structural process models, the structured elements are still sub-processes of an overall process, and not so much objects or system components. But at a later stage of system development, the process elements are often used to search for system components that might be able to perform the desired processes. Especially in the development of processing systems (e.g. a manufacturing line that processes other artifacts), this may result in an artifact system that can be represented by a structural model showing close resemblance to the original process model.

There are many examples of structural artifact models closely related to structural process models — e.g. the organ structure according to Hubka, V. and Eder, W.E. (1988), containing symbols for gearings, valves, pumps etc. as well as connections between them. In Ulrich, K.T. and Seering, W.P. (1989), several examples of similar models can be found. None of these models can be smoothly derived from one of the structural process models. The leap from process model to artifact model is expected to be performed through human creativity. Once they have been created, some of the structural artifact models allow for process simulation, resulting in process representations like time-related variable listings, time related graphs and graphical animations — representations that cannot be related to the original structural process model.

In artifact or process models representing processing systems, it is important to note the distinction between the processing system being the artifact system represented in (or related to) the model in the first place, and artifacts that are processed by the system and that may appear, for instance, as input and output of sub-processes. In a structural process model that is created to prescribe the processes to be performed by a new artifact system, the potential for artifact representation does not apply to the artifact system itself but to the artifacts that are processed by the system. On the other hand, if we are developing an artifact and we want to describe the production process of that artifact, we can apply the artifact representation potential of structural models to the artifact itself.

5.3 Primarily logical process models

A combined process model with emphasis on logic is the Petri net (e.g. Kiritsis, D. et al. 1998). Petri nets are especially useful for modeling processes in which the process elements are state transitions, requiring the achievement of a particular state in a system (or a combination of states) before the advancement to a subsequent state (or a combination of states) can take place. Petri nets were originally used for low-level modeling of digital systems but they can, for instance, also be used to manage complex organizational processes in which tasks are only allowed to start if certain other tasks have been completed (McMahon, C.A. and Xianyi, M. 1996). The Petri net of the process must be known in advance, therefore it is either based on historical knowledge of the same process or on presumptions about the course of a new process. Besides of being logical models, Petri nets address structural aspects (e.g. connections expressed by output states of a transition being the input states of another transition), functional aspects (the transitions are usually represented by verb-noun combinations) and behavioral aspects (limited to predictions if certain states will or will not be accomplished).

An artifact can be represented in a Petri net through the states that it can assume. In that case, we can include references to the artifact or parts of it in the identifiers of states and transitions. An example of this can be found in Suto and Kawakami's Physical Causal Network, which is based on Petri nets for explaining the behavior of artifacts in a qualitative way (Suto, H. et al., 2000). The artifact related states in a Petri net may be quantitative but due to the discrete character of Petri nets, continuous state transitions cannot be included as such. This is also a limitation where the process representation is concerned.

The complexity of artifact representations in Petri nets is arbitrary: the state transitions may as well apply to details as to compound systems.

5.4 Primarily functional process models

There are many process models with a primary focus on functionality. Especially the function block diagram (e.g. Kuttig, D., 1993) and its varieties are widely accepted in engineering, for instance the input-output diagram, the Activity Network and the Function Chain (Otto, K.N., 1996), General Function Structure (Hubka, V. and Eder W.E. 1988), Koller's 'Teilfunktionsstruktur' (Koller, R., 1976) and

other similar models (e.g. Umeda, Y. and Tomiyama, T., 1997). These models are used in design of complex systems to facilitate the decomposition of the required functionality into manageable parts. The structural content of the models is not limited to decomposition; it also includes sequential relationships and input-output relationships.

Most functional process models in this group form part of a methodology for deriving an artifact system from an initial functionality description, but, as with the structural models, the leap from process representation to artifact representation is left to human creativity.

Tomiyama's FBS (Function Behavior State Modeling) strives to link the subjective notion of function to the objective notions of behavior and states (Tomiyama, T., 1993; Shimomura, Y. et al., 1996). The behavioral side of FBS is handled by applying Forbus' Qualitative Process Theory (see section 5.5). Although artifact and process representations appear together in one model, well-defined transitions between the two are not explicitly or implicitly supported.

A somewhat more primitive function model is the process tree which industrial designers often use to check the completeness of a list of requirements regarding the life-cycle of a new product. Apart from functionality, it only addresses the structural aspect of hierarchy and sequence within a process (Van der Vegte, W.F. et al., 2000).

Except for the process tree, the potential of including artifact representations in these functional process models is the same as in the structural process models discussed in section 4.2., only the FBS cannot include quantitative artifact information. The remarks concerning the distinction between artifacts that perform a process and artifacts that are being processed also apply to functional models.

For the process tree, the potential of including artifact representations is the same as that of the tree-like structures discussed in subsection 4.2.

5.5 Primarily behavioral process models

Most of the process models typically used in engineering have a focus on behavior. As was mentioned before, the mathematical equation can be regarded as the most elementary behavioral process model. Apart from representing temporal and behavioral aspects, equations can be enhanced with logical aspects by combining them with boolean expressions and inequalities. The potential of including artifact representations in such enhanced equations models is the same as in the time dependent equations discussed in subsection 4.1.

Models based on Forbus' Qualitative Process Theory (QPT) can cover the same temporal, logical and behavioral aspects as equations do (Forbus, K.D., 1984). But although such models represent time dependent behavior, the notion of time is not explicit. In QPT models, both artifact details and artifacts as parts of a larger compound are usually included in the names of quantities, which are supposed to be the equivalent of variables in equations. The exactness of artifact representations in QPT is, contrary to equations, always qualitative.

An different type of primarily behavioral process model is the bond graph, which can be used to predict time dependent system behavior based on energy flows (e.g. Redfield, R.C. and Krishnan, S., 1992). Basically, bond graphs can be regarded as structural representations of artifact systems. The components of the system are represented by basic physical characteristics, e.g. 'resistance', 'capacitor' or 'transformer'. Analogies between different domains of physics allow for using the same building blocks throughout hybrid systems built up from mechanical, electrical, hydraulic, etc. components. Potentially, a building block refers to the function of a component (e.g. 'to transform something') but it can also represent unwanted secondary behavior (e.g. friction as a form of resistance).

Especially in electrical and hydraulic systems, the components of a bond graph indeed directly correspond to artifact components. But in mechanical systems, the correspondence is not so clear. For instance, for every occurrence of friction in a mechanical system a resistance 'component' should be included, thus troubling the relationship between the bond graph and the artifact system. In such cases, the bond graph is merely a graphical simplification of the system of differential equations that lies behind it. The elements act as processes elements and the structure of a bond graph reflects a process structure.

As far as mechanical systems are concerned, bond graphs can include artifacts by naming and by means of artifact relationships, just like equations do. But unlike equations, Bond graphs seldom refer to artifacts on a detailed level.

Another primarily behavioral model is FEM (Finite Element Modeling or Finite Element Method), (Zienkiewicz, O.C., 1977). In FEM, the process is modeled 'through the artifact'. The actual representation that can be created and edited is a representation of an artifact: based on a structural approximation of its geometry, FEM can be used to predict its behavior.

This numerical technique was originally applied to static mechanical problems, but nowadays dynamical problems ranging from thermodynamics to magnetism can also be tackled using FEM simulations. In these more advanced applications of FEM in particular which are process related. We will address them as 'dynamical FEM' in the rest of this paper.

The process model behind FEM is a structured system of equations based on an assumption of energy minimization in the artifact. The structural composition and the complexity of the equations depend on the artifact model. The actual process model resulting *from* a dynamical FEM simulation is a representation describing the course of the variables considered relevant as a function of time (e.g. deformation, heat flow). The appearance of this process representation can vary from a time related listing of node values to a graphical 3D animation.

Since dynamical FEM is an artifact model in the first place, it has a pronounced potential for inclusion of artifact representations. dynamical FEM models typically address the artifact on a detailed level, but it can also be applied to particular compound structures, e.g. trusses built up from prismatic elements. It may be clear that FEM always represents the artifact in a purely quantitative way.

Unlike the modeling techniques discussed so far, dynamical FEM offers a smooth transition between an artifact model and a process model.

Apart from behavioral models based on the laws of nature, there are also behavioral models based on probabilistic assumptions of system behavior. They can especially be found in reliability engineering, concerning behavior related to failure, maintenance and repair. Instead of modeling the overall behavior of a component, a probabilistic function is put forward that exclusively focuses on *if* the component will behave, not *how* it exactly behaves. Ideally, the probabilistic function is based on empirical data on a given component. Typical process models used in reliability engineering are the FMEA (Failure Modes and Effects Analysis) table, the fault tree and the Markov diagram.

A typical simple FMEA table contains a list of functions, with for each function possible chains of causes for failure and estimates of the probability and the severity of each failure mode (Lee, B.H., 1999). A recent effort to include the overall behavior of components into FMEA is described in Eubanks, C.F. et al. (1996). Fault trees can be used to represent structural (hierarchical) and logical characteristics in failure chains. The Markov diagram focuses on state transitions, like the Petri net. It shows the possible states and transitions of a system with their respective probability of occurrence. It can be used for quantitative reliability prediction, e.g. in systems containing redundant components. The potential for artifact inclusion in FMEA tables and fault trees is the same as for the tree-like structures discussed in subsection 4.2. Markov diagrams offer the same potential for artifact integration as Petri nets do.

6 Discussion: to what extent can artifacts and processes be integrated into one modeling technique?

Figure 1 gives an overview of the process models discussed in the previous sections. It includes the process aspects covered and the potential for artifact inclusion.

Based on the issues investigated here, a list of criteria can be made to represent the highest possible level of artifact integration embodied in the collection of process models reviewed.

In the first place, the highest possible level of artifact integration can be denoted by the potentially included artifact content:

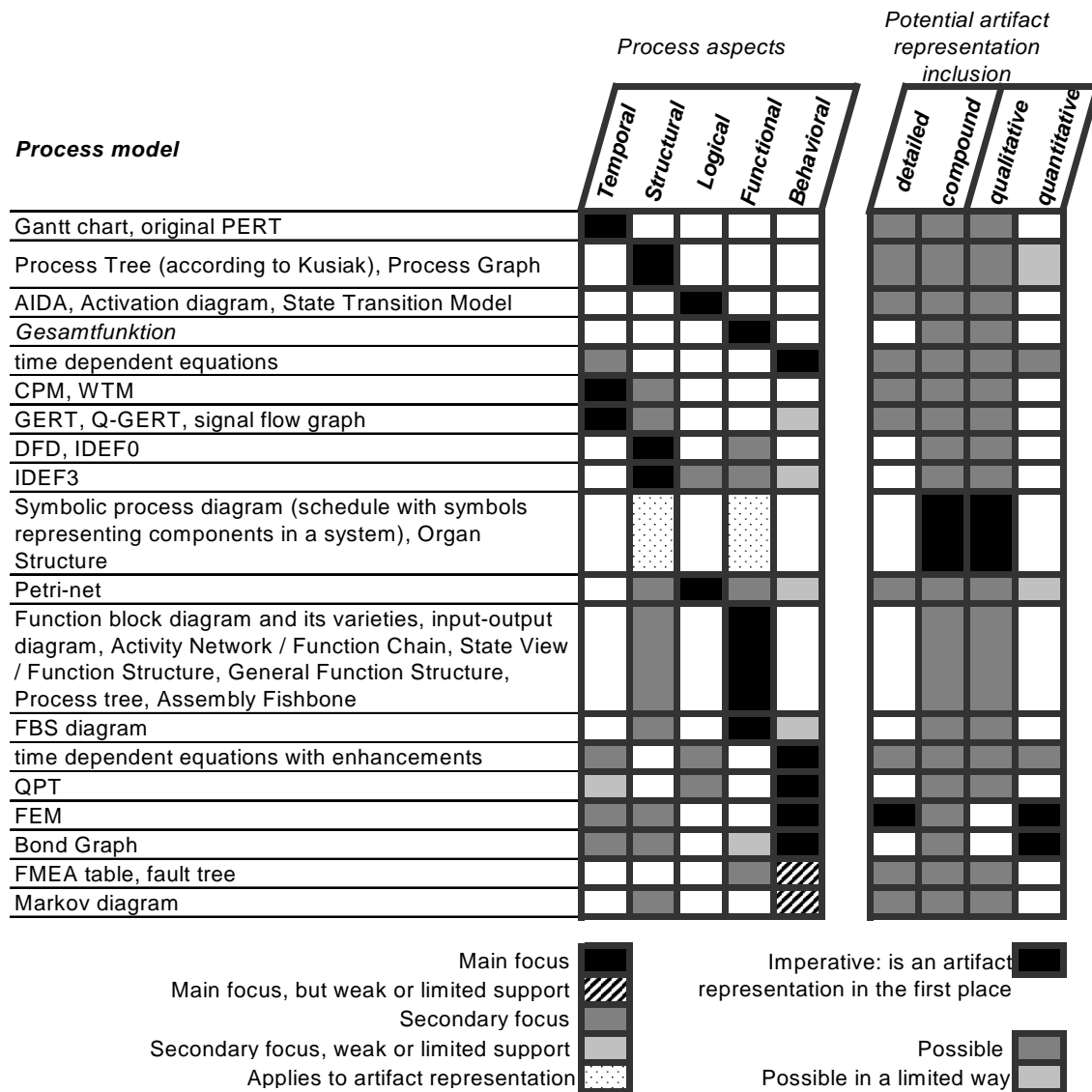
- 1) The process model should allow inclusion of artifact representations of arbitrary complexity, ranging from geometry detail to assembly;
- 2) The process model should allow inclusion of quantitative artifact knowledge.

In figure 1, it can be seen that several of the models reviewed here cover a broad range of complexity and that especially the inclusion of quantitative artifact knowledge is often not supported, or only in a limited way. In fact, only some of the behavioral models potentially offer full support here.

The other two criteria that should be applied, address the issue of transition between models:

- 3) The process model should explicitly support a smooth transition from process to artifact representation;
- 4) The process model should explicitly support a smooth transition from artifact to process representation.

Figure 1. Overview of process models



These criteria are perhaps even more important than the other two, because the two transition issues together express the need for a unified representation scheme, in which the distinction between artifact modeling and process modeling disappears into the background. After all, in real life, processes and artifacts are much more interwoven than the existing models suggest. For instance, building up a shape

during a design process can be considered a form of artifact modeling, whereas the activity itself is a process.

In the process models reviewed here, transitions from process to artifact representation are generally addressed by those structural and functional models that are part of a methodology for artifact system development. In all these cases, however, the actual transition is left to human creativity. If the process model is created and refined on a computer, there is no way to include knowledge about it in the artifact model that is built up after the transition.

The only smooth transition that could be found in the process models reviewed here, is the transition from artifact to process as it is produced by dynamical FEM. If we add to this that dynamical FEM meets both of the first two criteria it must be concluded that, of all the models reviewed in of this paper, dynamical FEM offers the highest level of artifact integration.

However, if a closer look is taken inside, dynamical FEM as a technique for actually integrated artifact process modeling has some weak points:

- 1) The transition between artifact and process representation is possible in one direction only. Obviously, if the behavior does not turn out to be as specified, it is not possible to edit the course of the process that results from the simulation, and then let FEM calculate an artifact geometry that performs according to the specifications. The artifact model must be changed based on human insight, and the process knowledge included in the previous output is not preserved in the computer system.
- 2) FEM can only handle physical processes in their strictest sense. Forbus, K.D. (1984) defines such a process as ‘a process in which the same influences hold over a distinct time’. A sequential combination of such processes (called ‘encapsulated history’ by Forbus), as it typically occurs in the life cycle of an artifact, requires a separately modeled simulation for each successive process. This is due to the quantitative nature of FEM. Transitions from one process into another process also include qualitative considerations that are out of FEM’s scope.
- 3) It is not possible to simulate different types of behavior (e.g. deformation and heat flow) simultaneously in one model.
- 4) Although the inclusion of quantitative artifact representations can be considered essential for reaching a high level of artifact-process-integration, FEM does not offer any support for qualitative analysis at all. This can be a drawback in those situations where not sufficient quantitative knowledge on the artifact is available, e.g. in conceptual design.
- 5) The energy minimization approach on which FEM is based does not correctly describe the processes *during* the discrete time intervals that are taken at a basis: FEM focuses on reaching the state of minimum energy at the end of the interval. In-between-effects, for instance oscillations, are ignored (Jansson, J. and Vergeest, J.S.M., 1999).

The inventory performed in this paper yielded one particular process modeling technique offering the closest integration with artifact modeling. It cannot be ruled out that an exhaustive state-of-the-art review may bring better candidates into the scene, which offer unexpected opportunities.

The procedure of ‘selecting a best candidate’ also assumes a particular *strategy* for artifact-process integration, namely that we should first identify one process modeling technique as ‘being the closest to artifact modeling’, and start integration from there. For instance, based on the scope of this paper, we could take dynamical FEM as a starting point. However, it can be questioned if this particular strategy is the most effective one. It is obvious that the other process models discussed here have their merits as well, some of them overcoming the disadvantages of dynamical FEM. It is for that reason that in a further inventory also the potential of mutual integration between process models should be explored.

7 Conclusions

The non-exhaustive literature search presented here showed that many existing process modeling techniques already offer potential for the inclusion of artifacts. The most prevalent bottle-neck for integration is to create modeling techniques that allow a smooth two-way transition between process models

and artifact models. One-way transitions from process to artifact could be found in the prescriptive functional and structural models that are used for systems development. But because these modeling techniques only provide an 'over-the-wall' approach for the transition, there is no potential for further inclusion of process knowledge in the artifact as soon as the transition has been made.

A transition in the other direction is offered by the dynamical Finite Element Method (FEM). This transition is well-defined and smooth, which may contribute to the popularity of dynamical FEM in professional engineering environment. However, dynamical FEM also has its limitations and it is not certain whether it is the ideal starting point for the development of an integrated technique for artifact-process modeling. Further investigation is needed; two topics that also need attention are (1) the strategy that is applied for the development of an integral approach, and connected to that, (2) the consideration if mutual integration of process models should be pursued as well.

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