TOWARDS A UNIFIED DESCRIPTION OF PRODUCT RELATED PROCESSES

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To increase the effectiveness of computer support in development and production of durable industrial products (artifacts), three problems still need to be solved: (a) integration of aspect models used in artifact development, (b) integration of the aspect models used in process planning and process representations, (c) integration of (a) and (b). This seems to be difficult, since different application fields, representation techniques and information contents have to be combined. It means that instead of the pure artifact and process models, we have to develop artifact-process models.

This article focuses on the integration of four kinds of typical life-cycle processes: (1) design (mental creation processes), (2) producing (physical creation processes), (3) operation processes (internal behavioral processes), and (4) use processes (external behavioral processes). In order to achieve a sufficiently high level of formalization in the computer-mediated handling of various processes, this article introduces a set-theory based representation. This representation makes it possible to stereotype the observed or forecasted processes, largely independent of their content. The applicability of the approach in real-life cases is demonstrated by three examples. Further research is oriented to the integration of process modeling with artifact modeling, as well as application to more complex cases.

Nomenclature

\[ P = \text{process} \]
\[ S = \text{set representing the domain of discourse of a process} \]
\[ \mathbb{R}^3 \times SO(3) = \text{configuration space of a rigid object in a 3-dimensional workspace} \]
\[ t = \text{point in time} \]
\[ T = \text{time interval} \]
\[ \tau = \text{time set} \]
1. Introduction

For a long time the development of computer-aided design systems concentrated on isolated representations of artifact related aspects—for example solid models (Ahab, 1990; Crocker et al., 1991) and finite element mesh models (Zienkiewicz, 1977)—and process related aspects—for instance bond graph models (Redfield et al., 1992) and Petri net models (D’Souza et al., 1994). Subsequently, development focused on integration of the aspects within the artifact domain [e.g. the STEP standard (Garrido et al., 1998)]. A current focus in research towards further improvement of the effectiveness of future computer support is the simultaneous consideration of the various aspects of processes. The unified formulation of processes, as it is presented here, takes place within the latter framework. It can be seen as a preparation for the next step, which is the integration of artifact and process aspects in a unified artifact-process model.

In particular, we focus on modeling the so-called life-cycle processes, or LCPs, which are assumed to play a role in the existence of a product (artifact). We distinguish the following principal categories of LCPs: (a) design or mental creation processes (b) production or physical creation processes, (c) operation or internal behavioral processes, (d) use or external behavioral processes, and (e) business processes in general. Referring to the integration with artifact modeling in later research, it is assumed that in business processes, the artifact typically appears only in an indirect way. Therefore business processes are not explicitly addressed in this research. In the other LCP categories mentioned, the artifact appears in a direct form, although for the mental creation process, the representation of the artifact remains abstract.

2. Objective and Scope of This Research

This research follows from the hypothesis that a better understanding, and consequently improved support, of new product development can be based on a formal description of life-cycle processes. The concrete objective is to devise a formalism that is independent of (1) the application domain and (2) the phase of the life-cycle considered. Eventually, we wish to achieve the following particular goals:

1. Descriptions of both actual processes and hypothetical processes and their characteristics using a unified representation, despite the heterogeneous types of processes
2. Explicit inclusion of time in the descriptions
3. A mechanism to categorize and subdivide processes
4. Identification of relations and dependencies between processes, in particular between artifact modeling and other life cycle processes
5. Performing comparisons between processes, as to find equivalent processes, reverse processes, concatenated processes, etc.
6. Identifying parallel, concurrent and interfering processes, as well as iteration, recursion and repetition.

A major issue we wish to address is the dependency between the first four categories of LCPs mentioned before, namely design, production, operation and use. Implicitly, this dependency plays a crucial role in product development. Hence, by using the formalism presented below to make this dependency explicit, we expect to gain understanding of—and control over—the execution and the management of product development.

A key element in this approach is looking upon properties of the artifact (or of the design model) as properties of a process that the artifact implies, executes or undergoes. For example, if the shape of a product and an ergonomic quality mutually influence each other, an improvement of the ergonomic qualities of the product can be translated into particular actions that should take place during design. This example
suggests a relation between a use process and a design process. In order to study these properties of—and relations between—processes we need a common formulation for all relevant types of process.

Finally, we remark that process descriptions as they are discussed in this article may refer to actually observed processes, but in the context of product development they will usually be forecasting models of processes not yet existing.

3. State of the Art and Related Research

With a view to future computer-aided design systems, a lot of research has already been conducted towards more effective process modeling representations. Progress has particularly been made in the areas (a), (b) and (c) mentioned in the introduction, and not so much in area (d).

Regarding (a), most research has been done towards scheduling and workflow management of development processes, including the prediction of durations (e.g. Smith et al., 1999). This kind of research is closely related to business process modeling in general (e.g. Schlenoff et al., 1996).

The same applies to research regarding (b), where control and management of operations are also leading topics (e.g. D’Souza et al., 1994)

Regarding (c), a lot of research has been done to simulate the behavior of objects on the level of material (e.g. Shapiro et al., 1999, Baraff, 1994). Furthermore, functional modeling in conceptual design is a widely covered area of interest (e.g. Kuttig, 1993). However, there is no clear link between the former, more detailed approaches and the latter, more general approaches.

Research in the field of use-process modeling (d) is still relatively immature (e.g. Chakrabarti, 1999), and the connection to computer-aided applications is still only existing in potential.

Research regarding the integration of more than one LCP category mainly concentrates on those processes that can be treated as business processes. A demonstrative example is Kusiak’s research on integrated modeling of design processes, manufacturing processes and general business process modeling (Kusiak et al., 1994). Other more or less integrated process modeling approaches tend to originate from a particular field of application, for instance, chemical plant engineering (e.g. Brice et al., 1999), aerospace engineering (e.g. Hale 1996) or architecture (e.g. Brown et al., 1995).

Summarizing the state of the art in product related process modeling, we can conclude that, in the first place, the areas of scheduling and workflow modeling for development and production processes are well ahead of the areas of operation and, especially, use-process modeling. Secondly, few attempts have been made to integrate modeling of LCP categories and to integrate modeling of different domains within one LCP category. Integration seems to be hampered by the need for dealing with

1. different application fields, for instance consumer durables, chemical plants, aircraft;
2. different representation techniques, for instance Petri-nets, Bond graphs, workflow schedules;
3. different information contents regarding the level of aggregation or segregation, for example material level vs. product structure level.

It can also be noted that the integration of process modeling with artifact modeling, which is planned as a further step in our research, is probably even stronger impeded by the diversity issue.

The research presented here is a first step towards the formulation of a general process model for LCPs. The proposed approach utilizes set theory as a starting point. Other product design related research with references to set theory can be found e.g. in Gorti et al. (1998) and Zeng et al. (1999). Gorti’s SHARED architecture focuses on representation of the artifact and the design process, as well as their mutual interrelations, and Zeng uses sets in equations, featuring the design requirements as known input variables and the design as a compound of the unknown outcome variables. They see the design process
as solving set-theory based equations. This approach is fundamentally different from ours in that Zeng focuses on particular deterministic design processes, in which the design merely is a selection from a catalogue of partial solutions. We propose a formalism in which this assumption is not needed.

### 4. A Unified Formulation of Processes

#### 4.1. General set-theoretic formulation of a process

In the following we adopt the formalism proposed by Vergeest and Van der Vegte (1999). The very essence of a process’ existence is that something changes. ‘Something’ can refer to almost anything: an object, a thought, an organism, a notion, etc. In a technological context, the term ‘system’ is often applied. To avoid going into the nature of ‘something’, we initially keep our definition as general as possible by stating that the changes take place within the scope of a set $S$, about which we will initially assume as little as possible. Intuitively, the term change refers to a time aspect: after the lapse of a time interval, something will be different.

**Definition:**

For given finite time interval $T$, a time set $\tau \subseteq T$ and arbitrary set $S$, the set $P \subseteq \tau \times 2^S$ is a process on \(\{T, \tau, S\}\) if $P$ is a mapping $P : \tau \rightarrow 2^S$, where $2^S$ is the power set of $S$ (the set of all subsets of $S$).

The process can be written as $P = \{(t, P(t)) \mid t \in \tau\}$. $S$ represents a Universe of Discourse, i.e., everything that is of interest to the description of process $P$.

$P$ is not defined on $T$ directly but on $\tau$ to avoid restricting processes to a connected time interval. Still we need $T$, so that we can restrict $\tau$ to a finite range in order to allow for a definition of start and finish of a process. As a matter of course, a process in which $\tau = T$ is a special case permitted by the definition.

Due to the assumed continuity of time, $P$ can be described as an ordered set of subsets of $S$. $P(t)$ specifies everything of interest at time $t$. Sometimes $P(t)$ is called ‘the state of the system’ at time $t$, a special interpretation implicitly suggesting that something called ‘the system’ is always observable in the process. However, the presence of something to which a ‘state’ can be assigned during the whole process is not a prerequisite. Another interpretation of $P(t)$ is to call it a snapshot of a process.

We now have defined a process as a time dependent selection from the universe of discourse $S$.

What this somewhat abstract set means for an everyday process can be illustrated straightforwardly: if $S$ is a geometric space, and $P$ selects exactly one point from $S$ at time $t$, then $P$ describes the motion of a point through space. If $S$ is the set of all possible temperature values of some object and $P$ selects only one value from $S$ at a time $t$, then $P$ may describe the course of the object’s temperature. If $S$ is the set of all people that ever lived, live or will live on Earth, and if $P(t)$ is the set of all people alive at time $t$, then $P$ describes the human population as a function of time. In the ‘Examples’ section, some demonstrative examples will be discussed in more detail.

#### 4.2 Characterization of a process

The characterization of a process $P$ explains how we can recognize a process as such. Intuitively, a process is characterized by the following attributes (to be defined in this subsection): (i) an initial element, (ii) a final element, (iii) intermediate elements, (iv) a start time, (v) a finishing time. Other possible characteristics of processes are (vi) whether they are idle or active, and (vii) its subdivision into sub-processes.
In the following definitions, the various constituents that characterize a process are further explained.

**Definition:**

For a given process \( P \) on \( \{ T, \tau, S \} \), we name \( (t_0, P(t_0)) \in P \) the initial element of \( P \) and \( (t_f, P(t_f)) \in P \) the final element of the process if \( t_0, t_f \in \tau \) and \( \forall t \in \tau : t_0 \leq t \leq t_f \).

All other \( (t, P(t)) \in P \) of \( P \) are called intermediate elements of the process. \( P(t_0) \) and \( P(t_f) \) are the initial and final sets of \( P \), respectively, and the remaining sets \( P(t) \) are the intermediate sets of \( P \).

\( t_0 \) is the start time of \( P \) and \( t_f \) is the finishing time of the process; \( t_f - t_0 \) is called the duration of the process.

\( P(t) \) is the range of \( P \). It is the collection of subsets of \( S \) that contains everything of interest at any \( t \in \tau \).

For \( \tau' \subseteq \tau \), \( P(\tau') \) is the image of \( \tau \) under \( P; \tau \) is the domain of \( P \). Closely related to the notion of activity and idleness of a process is that of invariance of the set on which a process is acting.

**Definition:**

\( S' \subseteq S \) is invariant under process \( P \) on \( \{ T, \tau, S \} \) if \( S' \subseteq \bigcap_{t \in P(t)} P(t) \).

Invariance can be used to recognize an idle process, i.e. a process in which nothing happens.

**Definition:**

Process \( P \) is an idle process if \( P(t) = P(t) \) for all \( t, t' \in \tau \).

If for \( P \) on \( \{ T, \tau, S \} \), \( S \) is invariant under \( P \) then \( P \) is idle. The definition of a sub-process is:

**Definition:**

For given process \( P \) on \( \{ T, \tau, S \} \), a process \( P' \) on \( \{ T', \tau', S' \} \) is a sub-process of \( P \) if \( P' \subseteq P \).

By definition, every process is a sub-process of itself. If we want to discuss what is happening in a process from a certain instant in time until another instant in time, regardless whether sub-processes are considered, we can use the process interval concept.

**Definition:**

For a process \( P \) on \( \{ T, \tau, S \} \), time interval \( T' \subseteq T \) and time set \( \tau' \subseteq \tau \) with \( \tau' \subseteq T' \), the mapping \( P' : T' \rightarrow 2^S \) with \( P'(t) = P(t), \forall t \in \tau' \), which is a process on \( \{ T', \tau', S \} \) is called a process interval of \( P \).

By definition, every process is a process interval of itself. In particular, the range of the process interval \( P' \) is equal to the image \( P(T') \). Also, a process interval \( P' \) on \( \{ T', \tau', S \} \) is a sub-process of a process \( P \) on \( \{ T, \tau, S \} \) if \( \tau' \subseteq \tau \).

Two processes that share the same time interval are called parallel processes. We can use the definition of a process interval to distinguish time intervals for which a process is idle or active. Note the difference between ‘an idle process’ as defined before and a process being idle for a certain time interval.

**Definition:**

Process \( P \) is idle for a time interval \( T' \) and a time set \( \tau' \subseteq T' \), if \( P \) has a process interval \( P' \) on \( \{ T', \tau', S \} \) which is an idle process. For all \( t \in \tau \) for which \( P \) is not idle, \( P \) is said to be active.
Definition:

The processes \( P \) on \( \{ T, \tau, S \} \) and \( P' \) on \( \{ T, \tau', S' \} \) are disjoint processes if \( P'(T) \cap P(T) = \emptyset \). Otherwise \( P \) and \( P' \) are called concurrent processes.

The key definition and the characteristics of processes given so far allow us to describe processes from different LCP categories as will be illustrated in the ‘Examples’ section. Only relatively simple process models were created based on this first version of the framework; the extensions required from further research in order to allow for more sophisticated process models can be found in the ‘Discussion’ section.

5. Examples

5.1. Example 1

To clarify the somewhat abstract general definitions, we will illustrate them by defining three simple models of regular life-cycle processes. In this first example we will apply the formalism to a mental creation process: realizing a simple sketch during conceptual design of a product. We will set up this model from the more abstract process of a point or a body moving through space. To start with, this abstract type of process will be described by a limited version of the process description, demonstrating that power sets are not always a prerequisite constituent of a process description.

A trajectory of a moving point in \( n \)-dimensional vector space is commonly defined by the set \( \{(t, P(t)) \mid t \in T\} \), where \( T \) is a finite time interval and \( P : T \to \mathbb{R}^n \) is some mapping (or function) from \( T \) into the vector space. The trajectory can be specified by \( n \) scalar functions on \( T \). It is important to notice that

\[
P \subseteq T \times \mathbb{R}^n.
\]

The domain of \( P \) is \( T \) and the range of \( P \) is denoted by \( P(T) \), which is a subset of \( \mathbb{R}^n \), namely the point set constituting the trajectory. Sometimes \( P(T) \) is called an ordered set of points in \( \mathbb{R}^n \). It depends on the mapping \( P \) whether the trajectory resembles what is informally known as a continuous curve.

\( P(T) \) could as well be one single point or infinitely many scattered points. However, it can be shown that \( P(T) \) can never occupy the entire space \( \mathbb{R}^n \); \( P(T) \) is restricted to a so-called dimensionality 1 object, due to the fact that \( T \) is equivalent to a line segment. We can view the mapping \( P \) as a process that fully describes the properties of a point in \( \mathbb{R}^n \) during the time interval \( T \). When \( P \) would model the behavior of a projectile, \( P \) is a process, describing what happens to the location of the projectile during its flight. (Note: for \( n = 3 \) and \( T = (-\infty, \infty), T \times \mathbb{R}^n \) is commonly known as the Minkowski space).

We can generalize the trajectory to the behavior of a subset of \( \mathbb{R}^n \), rather than of a single point, during the time interval \( T \). The mapping is then

\[
P : T \to 2^{\mathbb{R}^n},
\]

where \( 2^{\mathbb{R}^n} \) is the set of subsets (or power set) of \( \mathbb{R}^3 \). The simplest application of \( P \) is still the description of the motion of point, e.g. for \( n=3 \), but now the description is in conformance with our definition of a process. However, we can also model the motion of a rigid body through \( \mathbb{R}^3 \) using the same mapping. Additionally, more complex processes such as geometric deformation and fragmentation can be described. Note, that for a continuous movement of the object, the subset \( \tau \) may be equal to the time interval \( T \) itself.
The LCP of realizing a two-dimensional sketch (Figure 1) can be treated as a point moving along a trajectory in an $n$-dimensional space with $n = 2$ and the position of the point representing the position of the sketching pen on the two-dimensional sheet of paper. The sketching process can thus be described using

$$P: T \rightarrow 2^S$$

with $S = \mathbb{R}^2$, although in this case the expression $P: T \rightarrow \mathbb{R}^2$ would also suffice, unless more than one designer is working on the same sketch at the same time.

If we would say that Figure 1 is a snapshot of the process of sketching at $t = 120$ time units from the moment sketching started, we can say that $P(t) = P(120) = (14.7, 19.4)$, representing the values of $(x, y) \in \mathbb{R}^2$ as indicated in Figure 1.

5.2. Example 2

An entirely different LCP related process that we can describe using $P: T \rightarrow 2^S$ is the assembly of a product. To keep the description simple, let us take the example of a pencil sharpener as shown in Figure 2, which consists of three parts $m_1$, $m_2$, and $m_3$: a pencil holder, a blade and a screw respectively. Let us assume that assembly worker $w_j$ has the task of moving $m_i$ from an initial position to the assembly table and putting the blade in its position. Worker $w_2$ has the task of inserting the screw and tightening it with a screwdriver. An additional worker $w_3$ is available in case either $w_j$ or $w_2$ is unavailable. The tools (utilities) are named $u_j$ and $u_s$ for the table and the screwdriver respectively. The position of the parts $m_i$ is given by their coordinates $(x, y, z)$ in $\mathbb{R}^3$. The orientation of $m_i$ is given by angles $(\alpha_i, \beta_i, \gamma_i)$ in $SO(3)$. $\mathbb{R}^3 \times SO(3)$ is the configuration space of one rigid object in a 3-dimensional workspace.

The set $S$ will now be more diverse than in example 1. It may be defined as

$$\mathbb{R}^3 \times SO(3) \cup W \cup U,$$

where $(\mathbb{R}^3 \times SO(3))^3$ represents the configuration spaces for the three parts. Note that in this particular case only one point of each configuration space applies to a $P(t)$, although the power set of $(\mathbb{R}^3 \times SO(3))^3$.
would allow for any subset of each configuration space;

\[ W = \{ w_p, w_x, w_y, w_z \} \]

the set of assembly workers available, and

\[ U = \{ u_p, u_x, u_y, u_z \} \]

the set of tools available.

Inclusion of \( M = \{ m_x, m_y, m_z \} \), the set of pencil sharpener parts, is not strictly necessary, because the parts are implicitly included in the configurations.

For the process depicted in Figure 2, we took \( x_i = y_i = z_i = \alpha, \beta, \gamma = 0 \) at \( t = t_0 = 0 \) for \( i = 1, 2, 3 \). The figure shows how the contents of \( P(t) \) change over \( T \) (in this case, again, \( T = \tau \) ) from \( t_0=0 \) till \( t=43 \) time units. We can see that for the first part of the process, only \( (x_p, y_p, z_p) \) and \( (\alpha, \beta, \gamma) \) are changing, because worker \( w_j \) (see ‘other elements of \( P(t) \)’ at the bottom of the figure) is moving the pencil holder from its original location to the assembly table \( u_j \), which involves translations and rotations. The other parts are remaining in their original position. Shortly after the pencil holder has reached its location and orientation on the assembly table and remains there for the rest of the process, we see that \( w_j \) is manipulating the blade from its original location to its destination on top of the pencil holder, so that the final value of \( z_j \) is somewhat higher than the final value of \( z_j \) in the previous assembly step. For \( t=20 \), the contents of \( P(t) \) are shown as a ‘snapshot’ showing the coordinates and the rotation angles for all parts: \( m_i \) is at its position on the assembly table where it will remain until the end of the process; \( m_2 \) is being manipulated by \( w_2 \) using the assembly table \( u_2 \) and \( m_i \) is still at its original location. After the second assembly step it can be seen that the process interval \( P^* \) on \( \{T, \tau, S\} \), with \( T = \tau = [29, 32] \), is an
idle process and that \( P \) is idle for the time interval \( T' \), apparently because \( w_j \) is waiting before he picks up the screw. Then, after \( t = 32 \), the manipulation of the screw \( m_j \) is shown, falling apart into two stages: first there is the somewhat arbitrary movement of the screw to its insertion point by worker \( w_p \), which is very similar to the manipulation of the previous two parts. Then, at the bottom of the figure we can see that \( w_j \) starts applying the screwdriver \( u_j \), and for the screw only the coordinate \( z_j \) and the angle \( \gamma_j \) are changing: a constantly increasing rotation around the \( z \)-axis is making the screw go down into the pencil holder and fixing the blade onto it. Thus arriving at the end of the assembly process, we will finally have to conclude that, apparently, worker \( w_j \) has not played an active role in it.

5.3 Example 3

Now let us examine another process related to the pencil sharpener, namely the process of sharpening a pencil during the actual usage of the sharpener. Again, we keep the description of the process simple; although more complex descriptions can be put together to deal with the process in a more sophisticated way. The pencil sharpener can now be considered one entity, so we could refer to it by a single combination of coordinates \((x_p, y_p, z_p)\) and angles \((\alpha_p, \beta_p, \gamma_p)\) in \( \mathbb{R}^3 \times SO(3) \). Note that in this particular case, again, only one point of the configuration space applies for a \( P(t) \), although the power set of \( \mathbb{R}^3 \times SO(3) \) would allow for any subset of the configuration space;

In the sharpening process, naturally, a pencil is involved as well. We could represent it with coordinates and angles too, but that would not be sufficient for modeling that the pencil undergoes a destructive treatment in which parts of it are separated from its original shape. As an alternative, we can represent the pencil by regions in \( \mathbb{R}^3 \) corresponding to the space covered by the pencil itself as well as its residue. This is the same representation as discussed with the movement of a rigid body in Example 1. Apart from the sharpener and the pencil, there is also a user involved. To keep the description simple, we can represent him as a set containing only one element, \( \{ u \} \), just to indicate his involvement in the process.

The set \( S \) in \( P:T \rightarrow 2^S \) could now be depicted as \( S = \mathbb{R}^3 \times SO(3) \times \mathbb{R}^3 \cup \{ u \} \), in which \( \mathbb{R}^3 \times SO(3) \) represents the configuration of the pencil sharpener, the second \( \mathbb{R}^3 \) represents the space occupied by the pencil and its residue.

6. Discussion

The pencil sharpener examples forecast that it is possible to use the proposed process formalization to model product related processes from different LCP categories. Although this seems to be promising prospect, it is not yet proven that the entire life cycle of a product can be modeled in full detail. This is mainly for the following three reasons: (a) the examples were deliberately kept simple and some of the more subtle aspects remained uncovered; (b) some phases of life cycle, such as the conceptual design process, the part manufacturing process etc. have not yet been dealt with; (c) the process descriptions are not connected: even the same notions were addressed differently in the two examples.

Concerning these three issues, the following considerations apply:

(a) The simplicity that is allowed for a model depends on the context in which the reasoning takes place and on the phenomena one wants to take into account. For instance, depending on the modeling objective, in the assembly example it could have been possible to include the body configurations of the worker or the forces and torques applied to the screwdriver. In this case we assumed that these can be derived from the elements included in the model, because they were used as the starting point for reasoning about this process. However, it would have been
possible to include them in $S$ anyway, resulting in a model that can be considered over-complete. Such over-completeness can also appear for a part of the process only. For instance, while the screw in the second example is being fastened, there is a one-to-one relationship between its angle of rotation about the vertical axis and its vertical position. We could extend the process model with mathematical relationships to express this typical characteristic of screw threads, but we must keep in mind that this relationship does not apply to the free movement of the screw. In order to implement this effectively, some knowledge about the type of movement of the screw should also be included. The issues of completeness and enhancing the model with mathematical relationships will have to be addressed in further research. The extent of the completeness is also connected to the particular phenomena one is interested in. In the example of the sharpening process, the way the pencil was modeled can lead to misconceptions related to the notion of invariance: if the pencil is merely rotated, part of it keeps occupying the same space which would make it invariant according to the definitions. This is not a problem if the pencil behavior is considered a side issue only, but it is if one wants to study it intensively, for instance for optimization purposes. In such a case, a more complex definition of $S$ would be necessary.

(b) Especially the representation of those other processes in the life cycle in which the product itself does not yet exist in a physical sense are interesting where further research is concerned. This is most notably the case in the design process: can the modeling process be modeled and what is the relationship between the modeling process and the artifacts modeled during the modeling process?

Other issues for further theory development could be: classification of processes, predominantly based on the elements of which the set $S$ is composed, in order to establish a classification bearing significant relevance to the link with the artifact, as well as non-artifacts in $S$, such as information carriers. For this purpose, characterization of $S$ is needed, which is expected to augment the list of formalized common process terms with, for instance, input, output, performer. It is assumed that this will enable us to more effectively address the life-cycle processes we want to include in modeling activities associated with industrial products.

(c) In order to address this issue, the examples were deliberately not modeled in such a way that they could be directly integrated. However, in the sharpening process example we could have defined an $S$ including the three separate part configurations as we did in the assembly example. That, in this case, the positions and orientations of the parts would be closely linked, would perhaps make the model for the sharpening process more complex than strictly necessary, but for integration of the two processes into one model this certainly would have made sense. This implies, that in further research the topic of modifying the process set $S$ for the purpose of integrating process models into one over-all process should be addressed.

Additional issues for further theory development include the definition of additional properties commonly associated with combinations of processes, such as (i) decomposition into sub-processes (ii) interactions between (sub)processes and mutual dependency, (iii) objective, performance and convergence of a process.

7. Conclusions

The set theory based formalization of processes presented in this article offers a context in which processes of very different nature can be described, as is illustrated by the examples given. There is no prerequisite regarding a particular application domain or type of processes. The process set $S$ allows us to include common notions from systems theory, but it does not force us to designate ‘a constant something’
that is supposed be present during the entire process. This suggests that the formalism can be used for LCPs featuring multiple systems with shifting roles; for instance the roles the following ‘systems’ play in a product’s life: the design department, the production factory, the distribution system, the end user and, of course, the product itself.

The results up till now are sufficiently promising to continue this approach; it is indicated that the achieved status raises further topics for a more profound formalization of processes and inclusion of the formalism in computer-aided artifact modeling, eventually giving way to the integration of process elements in a conceptual computer-aided design application.

8. References


