Processes Modelling in Civil Engineering based on Hierarchical Petri Nets

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ABSTRACT: Process modeling is a central aspect for the support of the network-based coordination of planning processes in civil engineering. Hereby, the planning processes are characterized by some significant aspects, especially the great complexity and the dynamical behavior. To master both, the complexity and the refinement of planning processes, appropriate hierarchical structured process models are necessary. This contribution provides a Petri Net based approach for hierarchical process modelling. The focus is on the formalism to ensure the structural and behavioural correctness of the hierarchical process models and a prototypic software implementation for hierarchical process modelling in civil engineering.

1 INTRODUCTION

In building engineering every state of design, planning, construction and usage is characterized by specific processes. These processes can be organized very efficiently with the support of modern information and communication technology. Within the research projects “ Coordination of Planning Processes in Geotechnical Engineering” (Darmstadt) and “Relational Process Modelling in Co-operative Building Planning” (Hannover), that are both part of the priority program “Network-based Co-operative Planning Processes in Structural Engineering” from the German Research Foundation (DFG), relational process models based on hierarchical Petri Nets have been defined and implemented.

2 PROCESS MODELLING WITH PETRI NETS

Petri Nets provide a mathematical formalism and a graphical representation based on the graph theory in order to model the concurrent and asynchronous behavior of a discrete system. The Petri Net theory origins from the PhD thesis of Carl Adam Petri (1962). Since then, various researches, extensions and improvements have been applied to the original Petri Net theory. The application of Petri Nets to process modeling and workflow management has been introduced by, e.g., van der Aalst (1998) and Oberweis (1996). Especially, the application of Petri Nets on civil engineering processes is explained in, e.g., (Rueppel et al. 2003) and (König 2004). The main reasons for modeling Civil Engineering processes with Petri Nets are:

- the graphical representation of the structure an marking
- the bipartite structure with places and transitions for modeling both planning states and planning activities,
- the token concept for modeling logical firing conditions and the flow of planning information within an engineering workflow
- the mathematical formalism for structural, behavioral and simulation analysis of engineering process models.

For a short introduction to Petri Nets see, e.g., (Aalst 1998), for a comprehensive introduction, e.g., (Reisig 1985) or (Baumgarten 1990) are recommend. As illustrated in Figure 1 Petri Net consists of places, transitions and arcs, with each arc connecting either a transition and a place or a place and a transition. The tokens reside on the places. Based on well defined rules the transitions can “fire” and thus let the tokens “flow” through the net.

3 HIERARCHICAL PROCESS MODELING

3.1 *Basic Idea of hierarchical process modeling*

The process structure covers all planning activities. Activities represent work packages carried out by planning participants within a prescribed time period. They are specified on the basis of planning schedules for components and connections.

3.2 *Structure*

The entire planning process of a project is decomposed into basic activities which are also called phases. Typical basic activities are the feasibility phase, design phase and construction phase. The directed relationships from one activity to a successive activity are specified by planning states. Activities and states form a bipartite directed graph which is called workflow graph.

The following rules are introduced to realize parallel or alternative execution of activities and states. These rules, illustrated in Figure 1, form the basis for checking the structural correctness of workflow graphs.

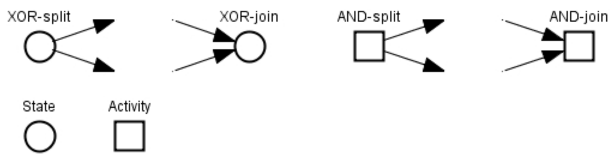


Figure 1. Rules for activities and states

A decision (xor-split) is modelled if a state has more than one successor. In this case only one of the following activities can be chosen and will be executed. A contact (xor-join) is modelled if a state has more than one predecessor. In this case the execution of exactly one of the predecessors must be guaranteed. An asynchronization (and-split) is modelled if an activity has more than one successor. In this case all following states will be executed. A synchronization (and-join) is modelled if an activity has more than one predecessor. In this case it must be guaranteed that all predecessors are executable.

Activities and states that are defined during the planning process can be specified in more detail. This recursive decomposition process leads to a process structure which is represented mathematically by a hierarchical bipartite directed graph.

$$P := (A, S; R, Q, f_{AT}) \tag{1}$$

with $f_{AT} : (A \cup S) \to (A \cup S)$

A	Set of activities
S	Set of states
R	Relations between activities and states
Q	Relations between states and activities
f_{AT}	Mapping for the composition of activities and states

The hierarchical bipartite directed graph is consistent, if a directed relationship on a higher level is associated with a directed relationship on a lower level and vice versa. For the correct execution of the activities the structural correctness of the process structure must be guaranteed. The process structure is correct, if there are no deadlocks and no lacks of synchronization.

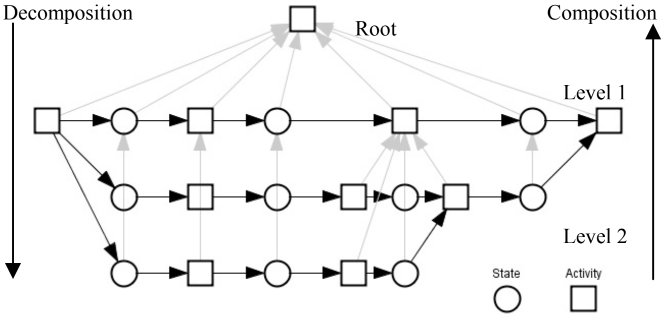


Figure 2. Hierarchical process structure

A deadlock as shown in Figure 3 arises, if after a decision alternative activities are merged by a synchronization. In this case the synchronization activity can not be executed.

A lack of synchronization as shown in Figure 3 arises, if asynchrony activities are merged by a contact. In this case the following activities would be executed more than once.

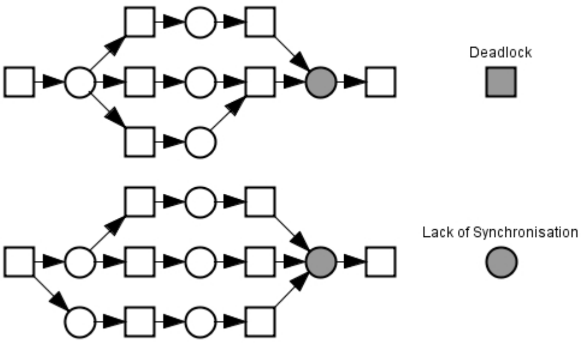


Figure 3. Deadlock and lack of synchronization

Deadlocks and lacks of synchronization are detected by hierarchical instance sub graphs which were introduced by van der Aalst (2002b). Every hierarchical instance sub graph describes one possible workflow without decisions. An algorithm for building hierarchical instance graphs is presented in (König 2004).

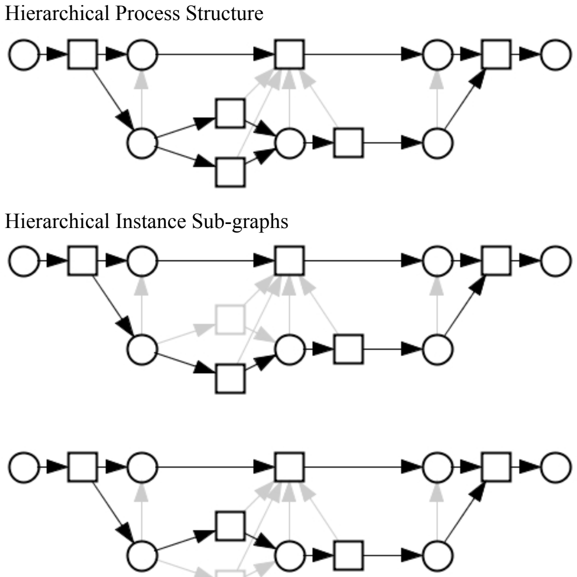


Figure 4. Hierarchical instance sub-graphs

3.3 *Critical Path Method*

The observance of time schedule for the planning process is very important. If an activity is not completed by a certain time the whole planning process could get delayed. The planning and observance of a time schedule is one important task for process modelling. For time scheduling the critical path methods can be used. They can be transferred in generalized form to bipartite graphs. The consideration of the hierarchy requires additional consistency conditions.

For each activity a participant needs a certain time to finish. Therefore each activity is labelled with a positive real time value.

A state specifies a relationship between activities. For time scheduling different types of relationships are defined. For a planning process it is sufficient to describe a state with a minimal time lag between predecessor and successor activities. If the time lag is negative these two activities can be handled parallel. If the time lag is positive a waiting time between these activities exists. Each state is labelled with a real time value.

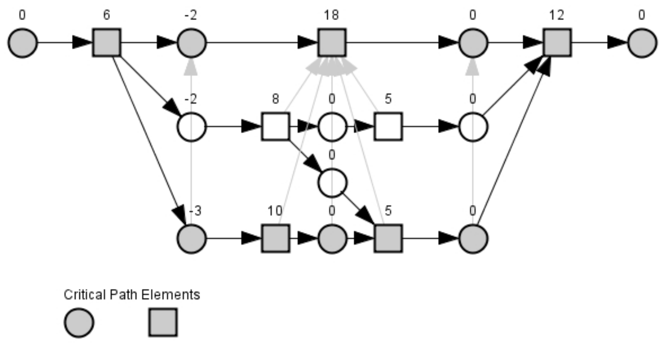
For critical path methods the hierarchical directed bipartite graph is extended by a label mapping for activities and states.

$$P := (A, S; R, Q, f_{AT}, w) \tag{2}$$

with $w : (A \cup S) \to \Re$ and $w(A) \subseteq \Re_0^+$

P Labelled process structure
w Labelling of activities and transitions

The critical path for each level of the hierarchy of a labelled hierarchical bipartite graph can be calculated with the well-known critical path methods. If the hierarchical graph is consistently labelled, the length of a critical path on an upper level is an upper bound for the length of a critical path on a lower level.



Critical path on the upper level: 34
Critical path on the lower level: 30

Figure 5. Consistent labelling of a hierarchical process structure

The consistency of the labelling has to be verified. For each decomposed sub-process of an activity on a lower level there is a labelled bipartite partial graph. The labelling is consistent if the critical path length of the partial graph is not greater than the labelling of corresponding activity.

$$w(x) \geq P(x) \tag{3}$$

w(x) Label of *x*
P(x) Length of critical path in partial graph

3.4 *Petri Nets*

For the process structure the methods of simple Petri nets are used to realize an event oriented communication. The hierarchy leads to additional conditions for the consistent marking of the process structure.

Each activity is in a certain state at any time. For an event oriented communication two different states of an activity are defined: not completed and completed. Each activity is marked by 0 (not completed) or by 1 (completed).

A state is active if all predecessor activities are completed and all successor activities are not completed. Each state is marked by 0 (not active) or by 1 (active).

For the application of simple Petri nets the hierarchical process structure is extended by a mapping for the marking of the activities and states.

$$P := (A, S; R, Q, f_{AT}, m) \tag{4}$$

with $m : (A \cup S) \to \{0,1\}$

m Marking of activities and states

The marked process structure is extended by exactly one start state and exactly one end state. The initial condition of the marked process structure is defined as: each state without predecessors is marked with 1 and each state with predecessors and each activity is marked with 0.

The consistency of the marking of a hierarchical process structure has to be checked. Each decomposed activity is completed, when all activities of the decomposition are completed.

The consistency conditions for states are based on the firing rules of transitions in Petri nets. These conditions can be described in vector and matrix form. With the initial marking of states and the actual marking of activities the actual marking of states can be checked.

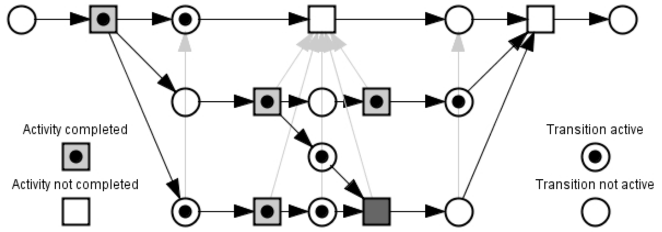


Figure 6. Consistent marking of a hierarchical process structure

An event oriented communication for planning processes is supported by a marked hierarchical process structure and Petri net methods. An activity can start if all predecessor states are active. Thereupon the planning participant is notified. If the participant reports the completion of an activity, the activity is marked with 1. The marked hierarchical process structure has to be updated.

Planning decisions obstruct the automation of an event oriented communication system. If a decision state (xor-split) is active the automatic process flow has to be stopped. The obstruction of the process has to be solved interactively by a participant with an appropriate role. If one of the successor activities is selected to be executed the associated participant can be notified.

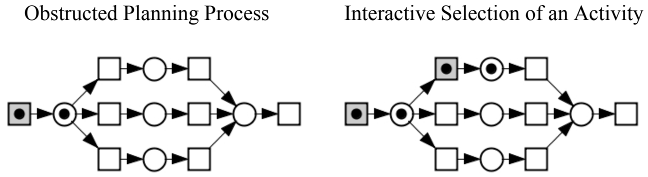


Figure 7. Marked process structure with a decision situation

4 PROMISE

Hierarchical process models are important for the computer aided support of engineering planning processes. This hierarchical concept facilitates the handling of large process models which are typical in engineering. Based on hierarchical process models the complex processes (e.g. planning processes, construction processes, maintenance processes) can be modeled by using a distinct number of detailed but small process models which are related to each other by a superior coarse process model. Depending on the level of detail, these process models can be generated independently by distributed technical engineers (Rueppel et al. 2004). Moreover, predefined process models, so-called process patterns (Katzenbach/Giere 2004), which have been applied during preceding projects can be used and adapted to the conditions of the current project.

ProMiSE is a software tool to support process modeling, process analysis and process control based on Petri nets. In the following, the focus is on the process modeling phase, i.e. the construction of a computer enabled hierarchical model of the real word processes. The theoretical background for the generation of hierarchical Petri net based process models - as implemented in ProMiSE - is presented by Kurt Jensen (Jensen 1996). Generally, it is possible to refine planning states and/or planning transitions. However, a refinement of transitions is recommended and reflects a more intuitive way of hierarchical process modeling.

When adding a sub-process to a planning activity in ProMiSE, the input and output states of the corresponding transitions are copied to the sub-process model. Figure 8 illustrates how to add a sub process to a planning activity

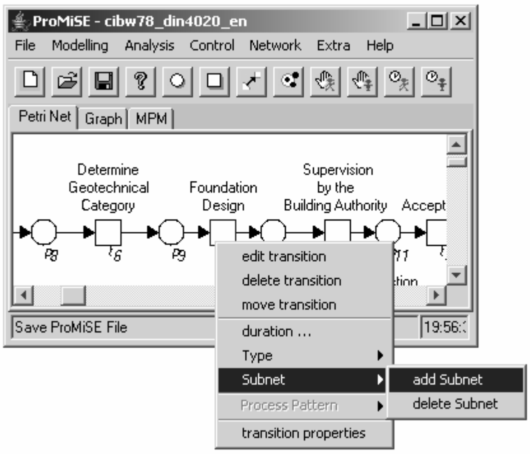
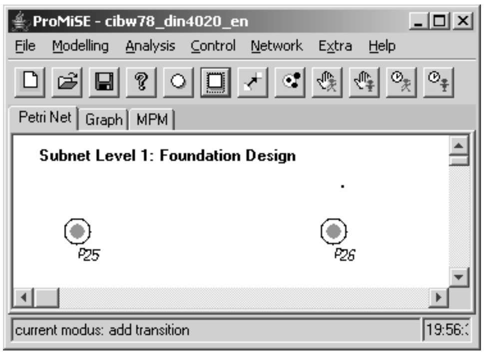


Figure 8. Refinement of a transition modeling a planning activity.

Figure 9 illustrates the initial state for modeling a sup-process. Hereby, the places (p_{25} and p_{26} in figure 9) are reference to the input and output places of the transition to be refined. These places define the interface between the superior process and the sub process. They declare the input information/condition as well as the output information, i.e. the result of the sub process. Having a precise definition of input and output information, is especially of great importance, if the hierarchical process models are generated by different and distributed planning participants. Furthermore these input and output place are necessary if a sub-process is realized by a pre-defined process model.



Subnet Level 1: Foundation Design

current modus: add transition

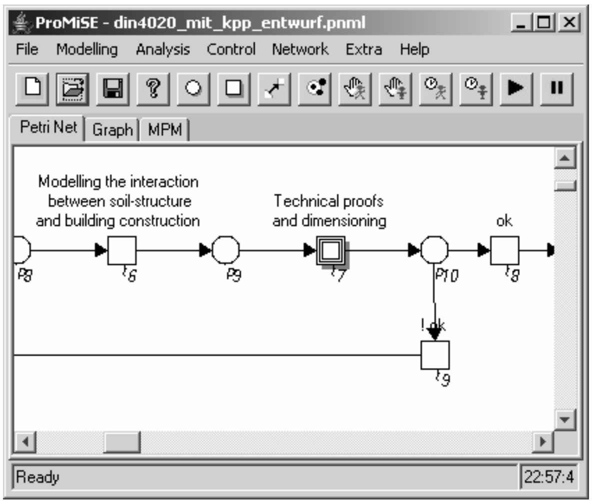
Figure 9. Initial state for modeling a sub-process.

5 PLANNING SCENARIO FROM GEOTECHNICAL ENGINEERING

To illustrate the hierarchical process modelling with ProMiSE by example, a typical design task in geotechnical engineering, namely the design a foundation for a building and the corresponding retaining wall for the excavation, will be modeled.

The top level process net within this example is a process according to the German standard DIN 4020 shown in Figure 10. This process model describes planning activities and planning states in order to design a foundation for a building and the corresponding retaining wall for the excavation. Therefore the focus of the process model is on geotechnical engineering with interactions to other technical domains, e.g., architecture, structural engineering or environmental approval authority or the building owner. At this level of detail, the process model provides an overview of activities without going into the technical details of each activity. The activity being refined is the transition t_7 “Foundation Design”.

The associated sub-process net provides the design process for a distinct foundation technology, e.g. a shallow foundation or a pile-raft foundation. The process model illustrated in Figure 11 is a part of the design process for a pile-raft foundation.

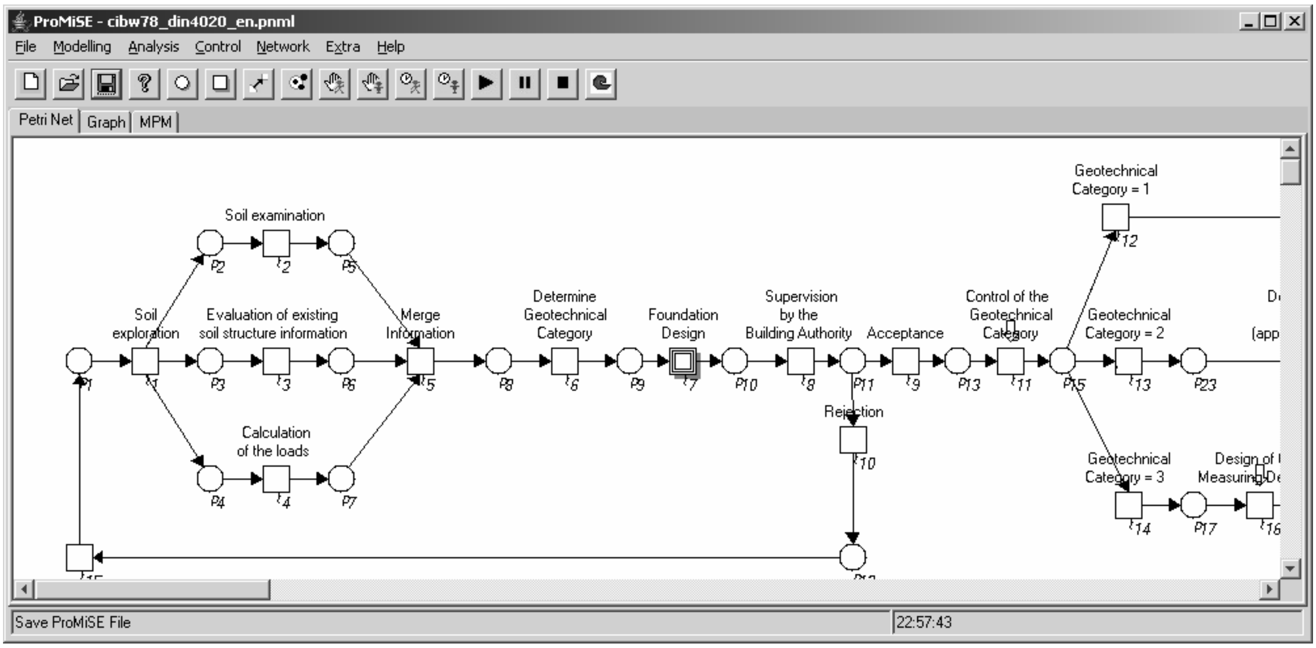


Ready

Figure 11. Design process for a pile-raft foundation (excerpt)

Depending on the result of the planning activity t_7 “Technical proof and dimensioning” the design process proceeds or an iterative planning process has to be initiated. Basically, this sub-process model contains parallel, sequential or conditional planning activities without going into detail of each planning activity. This is realized by further sub-process models.

Figure 12 illustrates the sub-process model of the transition “Technical proof and dimensioning” mentioned above. It provides detailed technical planning tasks in order to dimension a pile-raft-foundation. At this level of detail the sub-process model describes planning and dimensioning activities for a specific



Save ProMiSE File

Figure 10. Geotechnical planning process according to DIN 4020

foundation technology. Whereas the top level process model comprises different planning participants in this sub-process model it is only the geotechnical engineer who executes the modeled activities.

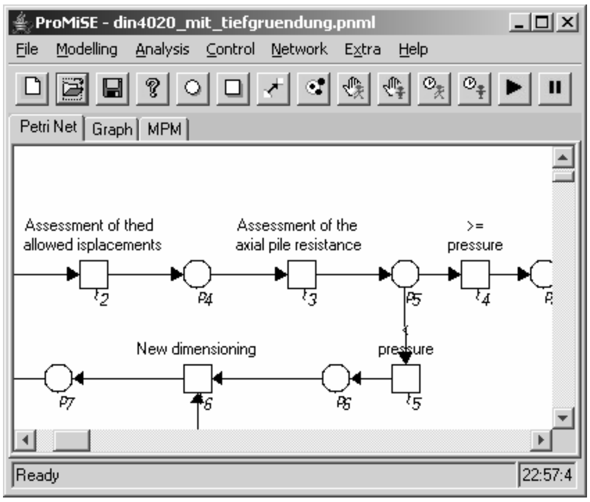


Figure 12. Technical proof and dimensioning process for a pile-raft foundation (excerpt)

6 SUMMARY

This paper presents a concept for a hierarchical Petri-net based process model for planning processes in building engineering as well as an implementation of this concept. The hierarchical structure of this model supports the dynamical aspects of cooperated planning processes in building engineering. The consistent and correct composition of the relational process model is very important. To ensure consistency and correctness of the compositions, conditions as well as methods for coordination and controlling of the planning process are formally defined.

The structures, conditions and methods have been implemented prototypically and were used in extracts for example projects.

The software tool ProMiSE supports process modelling, process analysis and process control based on Petri Nets. Within this paper the focus was on the definition of hierarchical process models and an exemplary scenario from geotechnical engineering modelled with ProMiSE.

7 ACKNOWLEDGEMENT

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