Journal of Universal Computer Science, vol. 15, no. 9 (2009), 1746-1765
submitted: 19/8/08, accepted: 25/4/09, appeared: 1/5/09 © J.UCS

Organizational Simulation of Complex Process Engineering Projects in the Chemical Industry

Sven Tackenberg, Bernhard Kausch, Sönke Duckwitz
Christopher M. Schlick, Selvinaz Karahancer
(RWTH Aachen University, Aachen, Germany
[s.tackenberg | b.kausch | s.duckwitz | c.schlick | s.karahancer]@iaw.rwth-aachen.de)

Abstract: The complexity of process engineering projects in the chemical industry – resulting from the large number of activities to be accounted for as well as the required actors and resources – and the number of projects running simultaneously within an enterprise are rapidly increasing. In order to stay competitive, the factors relevant to the success of project planning and execution, e.g. the project budget or duration, must be accurately predicted and controlled. For this reason, a novel simulation approach for development projects is introduced and validated. A formal description of a development project and of an activity-oriented simulation model is given. This "meta model" is able to describe the influencing factors of a development project as well as their interrelations during the course of a project. On the basis of the meta model, an activity-oriented simulation model is developed in cooperation with enterprises from the chemical industry. The simulation model enables the automatic creation and prospective benchmarking of complex, detailed project plans. The dynamics of such a development project are represented as a stochastic Petri net, including Java functions. Organizational factors of a development project such as task scheduling, the limited availability of actors and tools or uncertainty regarding the effort required to solve a task can be systematically studied through simulation experiments. The results of these experiments assist project managers in understanding the influence of the quantity and characteristics of actors and resources on project performance. In the validation study, a chemical process design project in a large enterprise is considered and the external validity of the stochastic project model is analyzed.

Keywords: Project Engineering, Petri Net Simulation, Formal Description of Development Projects, Collaborative Design
Categories: J.6, K.3, J.4

1 Introduction

The successful management of development projects in the chemical industry is an important source of competitive advantage. The developed chemical processes and facilities are unique among engineering artifacts in that they are often simultaneously capital cost intensive, operating expense intensive and are designed for long lifetimes [Biegler, 99]. An increasing number of companies are facing problems concerning budget and deadline overruns, missed specification, and consequently customer and management frustration [Huberman, 05]. As a result, novel methods for identifying, analyzing and optimizing the main influencing factors of a project as well as their interaction in terms of complexity and coherence are necessary [Schlick, 08]. It has been proved by practice that a scientific concept of project planning brings the following benefits to the enterprises: the lead time of the chemical process design is shortened through integration of distributed functions, applications, and organizations; design and production costs are reduced through effectively shared design and manufacturing resources; market response agility and customer satisfaction are improved through co-operation among project members like enterprises, customers, suppliers or individuals [Mahesh, 07].

The complexity of a development project results from different sources. [Kim, 03] developed a complexity template that covers many important sources. Not all of the sources mentioned by [Kim, 03] are relevant to development projects of the chemical industry. The first relevant source is "technological complexity". This source can be divided into "component integration" and "technological newness". The second source considered here is "development complexity" which is generated when many different research decisions and components have to be integrated, qualified suppliers found and supply chain relationships managed. "Organizational complexity" is the third source, as chemical process design projects involve many areas of an enterprise, particularly through the global value chain performance and the high level of automation [Foltz, 08]. Effective communication strategies and team organization are therefore required. The design projects of the chemical industry usually involve not only various areas of one enterprise, but also other companies. Their coordination during a development project leads to "intraorganizational complexity", the fourth source of complexity considered here. These four sources are very helpful as they cover many influencing factors that contribute to the specific characteristics of a development project. However, without a scientific concept of project dynamics the best project plan for a development project is only based on an arbitrary set of influencing factors. The project planner therefore never knows how the set of factors will affect the project performance.

Our approach proposes a simulation methodology to evaluate project complexity as well as organizational performance at the planning stage of a development project in order to enable the project planner to generate effective and efficient project plans for the purpose of improving the system dynamics. Development projects of the chemical industry often differ from projects of other industries in higher project budgets and therefore longer project durations and uncertainties regarding the course of a project and the number of involved actors and domains. Therefore we implemented an approach in strong cooperation with German project managers of the chemical industry which considers the characteristics of cooperation, communication and coordination processes of actors within development projects as well as industry-sector-specific uncertainties regarding the course of such projects.

2 Literature Review

The modeling and simulation of complex socio-technical systems – especially development projects – as a field of research is very heterogeneous. A good taxonomy for classifying simulation approaches from an industrial engineering point of view is presented by the German standard VDI 3633 [VDI, 01], Part 6. According to this standard, the pivot point is the actor's degree of personal action within a work process and the simulation models can be divided into activity-oriented and actor-oriented approaches. Both areas can be further differentiated as to the level of detail of human behavior represented in the model: task-centered, personnel-integrated, and person-centered.

In the considered domain of modeling and simulation of complex development projects, both the activity-oriented and actor-oriented approaches described below are important. To cope with the unpredictability and uncertainty of the design process, simulation technologies are widely used to predict, analyze and evaluate development projects. One important activity-oriented approach is based on the Design Structure Matrix (DSM), developed by [Steward, 81] to model the information flow of design tasks and to identify their dependencies. Later, many studies were carried out to model and improve product development processes based on the DSM method [Eppinger, 94], [Cho, 05]. [Yao, 06] developed a process model which combines the DSM model with activity networks and developed a simulation algorithm to predict and analyze the course and the performance of a project. An activity-oriented, task-centered simulation model to predict the impacts of alterations in development processes was developed and validated for a development project in the automobile industry by [Lukas, 07]. They integrated the impact of product changes during the development process on project duration and costs. It must be mentioned that most of the DSM based approaches do not consider the availability of actors and resources as a constraint [Eppinger, 94].

Other important actor- as well as activity-oriented approaches use Petri nets to model and simulate development projects by formulating task networks. For instance, [Kausch, 08] used extended stochastic high-level evaluation Petri nets to implement an activity-oriented approach. The target of their research is to simulate the design process in order to obtain a product development plan. [Krause, 04] use colored Petri nets in combination with stochastic procedures in order to sufficiently depict decisions regarding the course of the project during a simulation run. The planner first roughly models the activities of the development process; these activities are then further specified during the simulation run by accessing a database. The dynamic calculation of the model structure at cycle time adequately depicts the uncertainty-afflicted cycle of planning processes. [Tian, 04] introduced fuzzy timing high level Petri nets to model and analyze collaborative design activities. A set of reasoning rules and criteria are proposed to manage the uncertainty of temporal parameters in collaborative activities and to quantitatively evaluate the collaboration performance. Another activity-oriented approach to simulating product development processes was developed by [Raupach, 99]. It consists of four partial models corresponding to the requirements of a product development process: the main model, the activity model, the resources and organization model, and the data model. A comprehensive approach to an agent-based monitoring and controlling of workflows was developed by [Savarimuthu, 04].

Actor-oriented approaches, in which actors (the participating persons or organizations) determine the system behavior with the tasks specified for them are primarily investigated by [Licht, 07], [Levitt, 99]. Especially interesting research was conducted by Levitt's group. They developed a computational model of project organizations – the so called Virtual Design Team (VDT) – which simulates the micro-level information processing, communication, and coordination behavior of actors (participants) in a project organization and predicts several measures of participant and project level performance. VDT-1 [Cohen, 92] modeled project organizations containing actors with perfectly congruent goals engaged in complex projects. [Levitt, 99] further developed the VDT-3 to include measures of activity flexibility, complexity, uncertainty and interdependence strength. Besides the VDT, the simulation studies of [Licht, 07] focused on the actor-oriented, person-centered approach. Using Timed Stochastic Colored Petri Nets (TSCPN), [Licht, 07] were able to integrate the bounded rational behavior of product developers during a development project.

In summary, there have been only very few simulation approaches [Licht, 07], [Levitt, 99] that fulfill the requirements of describing the complexity of design projects in the chemical industry. Influencing factors particularly relevant to development projects in the chemical industry have not been considered. In particular degrees of freedom regarding the assignment of actors to tasks based on competence profiles as well as uncertainties of the makespan and the sequence of tasks are missing. Therefore new approaches for a simulation based project management in the chemical industry are required to measure the effectiveness of the project structure and the assignment of actors and resources to tasks to improve project performance. The focus of our approach is thus to generate a close analogy between the developed simulation model, real project structures and project performances. Hence, we aim at an activity-oriented, person-centered approach.

3 Methodology for Project Engineering

As shown in the previous section, simulation as a methodology is suitable for solving work-organizational problems. Hereby, the developed simulation model is integrated in a methodology for the organizational modeling, analysis and optimization of development projects. This methodology closes the gap between work-process modeling and discrete event simulation and thus enables a holistic improvement of the process organization. Therefore our approach corresponds to the tradition of industrial engineering science due to the development of an applied solution for project management. Thereby the paradigm that a simulation based a priori evaluation of alternatives results in more effective and efficient project organizations is the basis of the introduced simulation models [Licht, 07], [Levitt, 99]. The work of [Cohen, 92], [Levitt, 99] about the Virtual Design Team (VDT) as well as the studies of [Osborne, 93] are verifying the practice used in the simulation model below. Based on the requirements of investigated development projects in the chemical industry a formal description (meta model) of the influencing factors and their interrelations regarding the course of a project was developed. The meta model, introduced below, was the reference point for the conceptual design of a Petri net-based simulation model [Fig. 1]. The *Project Editor* provides a tool for the graphical creation and parameterization of work processes in complex development projects based on the C3 method [see Section 3.2]. For the developed framework, the *Simulation Tool* generates various project scenarios and therefore several courses of a project through the use of stochastic procedures [see Section 3.3]. The analysis tool shows the dependence between independent and dependent variables by means of performance charts.

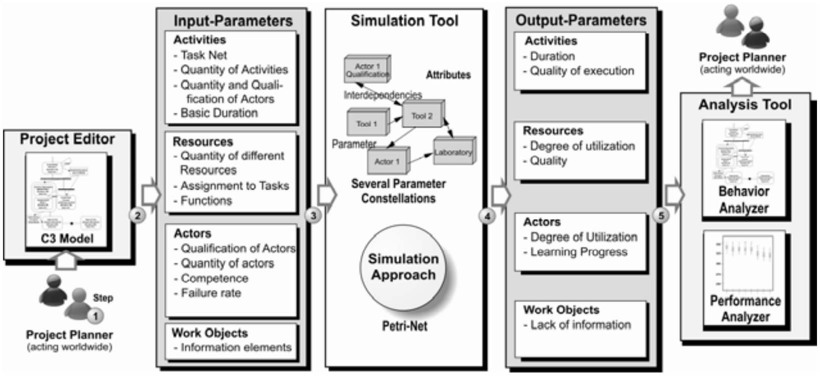

Figure 1: Simulation model for project engineering

3.1 Meta Model

The meta model for development projects of the chemical industry is based on the work system model of [Schlick, 07] and offers a systematic consideration of aspects relevant to simultaneous engineering. The elements of the work system according to Schlick as well as additional elements will be used to describe a consistent meta model of a development project [Fig. 2]. The meta model is the formal basis for the implementation process of the simulation model. To structure the integrated elements the meta model is divided into five partial models, which will be introduced below.

3.1.1 Partial Model of the Project Organization

An enterprise, *E*, consists of the union of m organizational units, OU_i:

$$E = OU_1 \cup OU_2 \cup OU_3 \cup ... \cup OU_m .$$

Each organizational unit, OU_i, consists of *n* actors (*Act*) with n≥1, where the set of all actors that belong to an organizational unit *i* is labelled Act_i:

$$OU_i = \{Act_{i_1}, Act_{i_2}, ..., Act_{i_n}\}$$

Each actor is unambiguously assigned to one organizational unit; i.e., the organizational units OU_i and OU_j do not have any mutual actors:

$$Act_i \cap Act_j = \varnothing.$$

An exception is the explicit authorization of an actor by the project manager/planner for *Tasks (TA)* in other organizational units. Therefore, all tasks within the projects to be planned (scheduling problem) are unambiguously assigned to the enterprise’s organizational units.

$$TA(OE_i) \cap TA(OE_j) = \varnothing \qquad i \neq j.$$

Considering simultaneously running projects, a task is assigned to one project. Thus, an activity must be labeled with a project ID. If P_l is the project ID of the activity A_i, then:

$$A_{i P_l} \neq A_{i P_m} \qquad l \neq m.$$

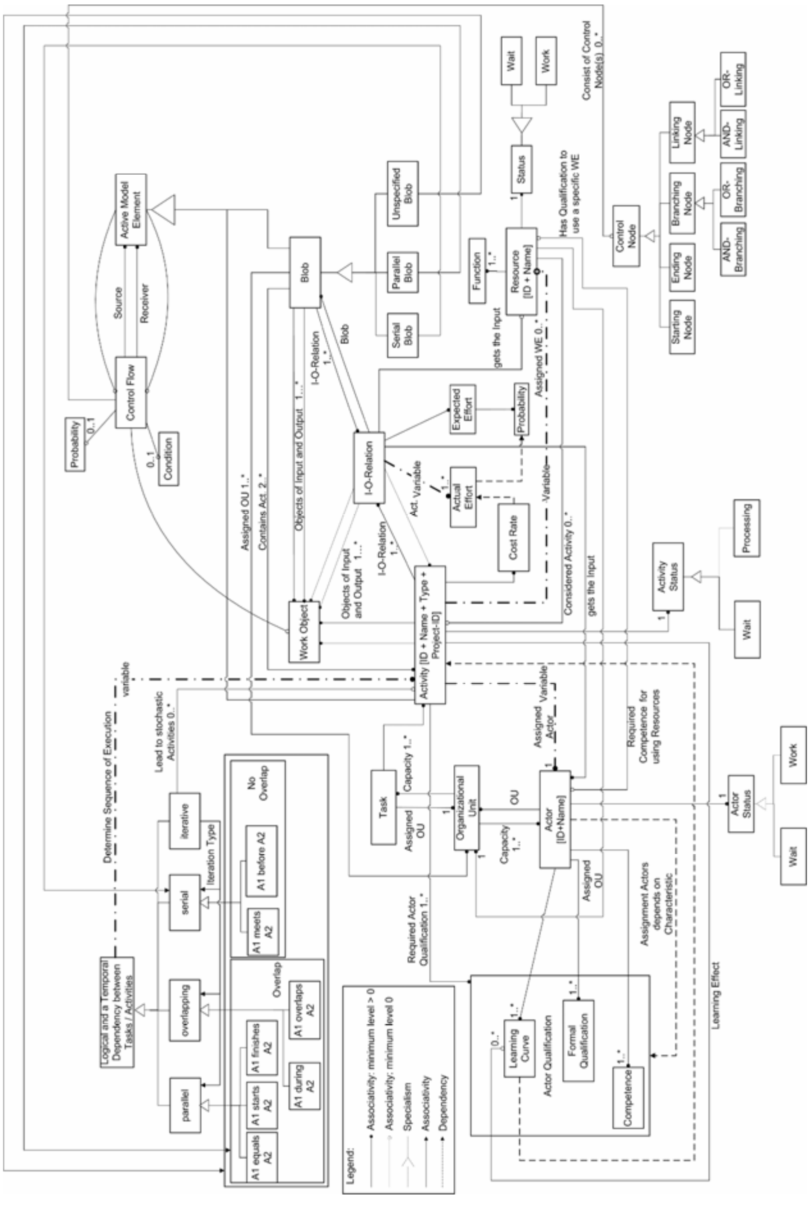

Figure 2: Meta model for the activity-oriented approach of development projects

3.1.2 Partial model of the Project Structure

The focus of the partial model of the "*Project Structure*" is the task that is transformed into an activity by being processed by actors and resources (tools and facilities). An activity is an active model element and represents a work step toward the achievement of the project goal set by the planner. An *Activity* A_i is characterized by:

S_{A_i} = Starting time of activity *i*

E_{A_i} = Ending time of activity *i*

I_{A_i} = Input of activity A_i

O_{A_i} = Output of activity A_i

$A_{i\,P_k}$ = Project ID *k* of A_i.

An activity is furthermore defined by mandatory (fixed) as well as variable attributes:

A_{fixed} = *{ID, name, type, project ID, organizational unit, input-output relation}.*

A_{var} =*{required actor qualification, required functionality of resources, assigned actors, input object, output object, cost rate, learning effect}.*

The formal definition of one Activity A_i also characterizes the multiplicity of the contained attributes:

- *= 1:* ID; name of activity; type; project ID activity is assigned to
- *= 1:* Organizational unit;
- *≥ 1:* Actor or required qualification
- *≥ 1:* Input object; output object
- *≥ 0:* Assigned resources; cost rate; learning effect.

Two statuses of an activity during a project progression can be distinguished: $A_{Status} = \{A_{Wait}, A_{Execution}\}$; Status $A_{Execution}$ represents an activity which is currently processed; (Status A_{Wait}) describes the waiting for requirements to be fulfilled before execution.

The predecessor constraints between tasks/activities indicate an organizational and a temporal dependency. Therefore, an activity, A_{i+1}, can only be carried out if the predecessor activity A_i was sufficiently processed. The predecessor constraints which determine the sequence of tasks/activities are either deterministic or stochastic. Four types of predecessor constraints between activities can be distinguished for development projects: *serial, parallel, overlapping* and *iterative*. Activities with a predefined sequence and in which predecessor activities must be completed prior the execution are termed *serial*:

- $A_1 \textit{ before } A_2 : E_{A_1} < S_{A_2}$

Activity A_2 cannot start until A_1 has ended.

- $A_1 \textit{ meets } A_2 : E_{A_1} = S_{A_2}$

Activity A_2 starts directly after the completion of A_1, meaning the ending time of A_1 and the starting time of A_2 are identical.

Tasks/activities without predecessor constraints are termed *overlapping* or *parallel*:

- A_1 *equals* $A_2 : (S_{A_1} = S_{A_2})$ und $(E_{A_1} = E_{A_2})$

Activities A_1 and A_2 start at the same time and end at the same time.

- A_1 *starts* $A_2 : (S_{A_1} = S_{A_2})$

Activities A1 and A2 start at the same time.

- A_1 *finishes* $A_2 : (E_{A_1} = E_{A_2})$

Activities A1 and A2 end at the same time.

- A_1 *overlaps* $A_2 : S_{A_1} < S_{A_2} < E_{A_1}$

Activity A2 starts after the beginning but before the end of activity A1.

- A_1 *during* $A_2 : S_{A_2} < S_{A_1} < E_{A_1} < E_{A_2}$

Activity A1 is carried out during the processing of A2.

The characterization of the project structure – branching and merging of parallel task chains – is described by control flow nodes. The following nodes are distinguished: starting node N_S, ending node N_E, branching (AND-branching $N_{branch\text{-}and}$ and OR-branching $N_{branch\text{-}or}$) and linking nodes (AND-linking $N_{link\text{-}and}$ and OR-linking $N_{link\text{-}or}$):

$$N = \{N_S, N_E, N_{branch-and}, N_{branch-or}, N_{link-and}, N_{link-or}\}.$$

Beside an activity a so called “blob” is another active element in the meta model. The definition of a blob is given by the C3 method [see Section 3.2]. A blob consists of at least two activities and is either a serial, parallel or unspecified blob. Activities of a serial blob must be executed in sequence without any predecessor constraints. A parallel blob consists of activities that do not have a fixed predecessor-successor relationship (equals, starts, finishes, overlapping and during) but must be executed concurrently to a minimum extend. If the sequence of an activity execution is completely unknown, an unspecified blob is used. A blob *B* is furthermore defined by following attributes:

B = {assigned activities, assigned organization unit, input-output-relation, input and output objects}.

The formal definition of a blob also characterizes the multiplicity of the attributes:

- ≥ 1: Assigned organizational unit
- ≥ 1: input object; output object; input-output-relation
- ≥ 2: Task/Activities.

Iterative execution of tasks can especially occur in weakly structured development projects including a high degree of uncertainty. Two substantial characteristics of iteration must be distinguished:

- Unscheduled events occur within the course of a project, i.e., the iteration has not been taken into consideration during the planning phase.
- The iteration has been taken into consideration during the planning phase of a project by the planners. Activating an iterative exercise of one or more tasks is described in the meta model through probabilities or a causal cause-and-effect chain. The iteration describes the relationship between two or more activities with the following features:
- $O_{A_i} \subseteq I_{A_{i+1}}, O_{A_{i+1}} \subseteq I_{A_{i+2}}, \ldots, O_{A_k} \subseteq I_{A_1}$

The successful execution of activity A_k and therefore the output O of A_k leads to an iteratively start of activity A_i or the execution of the termination condition. Attention must be paid to the fact that an iterative execution of tasks often results in a different characteristic or sequence of activities within the iteration process. In the meta model, this phenomenon is described by the relationship: *"Leads to stochastic activities"* between the elements *iteration* and *activity* – Multiplicity 0..*.

3.1.3 Partial Model of Actor

An Actor *Act* is, in analogy to the description of the activity, depicted by fixed as well as variable attributes:

Act_{fixed} = *{ID, name, project assignment, organizational unit}*
Act_{var} = *{qualification, assigned tasks/activities}*

An *Actor Act* is defined by:

- *= 1:* ID; Name; organizational unit (actor is assigned to)
- *≥ 1:* Project ID (actor is assigned to)
- *≥ 1:* Formal qualification Act_Q
- *≥ 1:* Competence Act_C; learning curve Act_L
- *≥ 0:* Qualification to use a specific tool or facility (resource) Act_E

The formal qualification Act_Q of an actor describes his or her ability to process a specific task on a certain quantitative and qualitative level [see Section 4.3.2]. The execution leads to an improvement of actor's competence regarding this specific task type. Thereby the learning aptitude of the actor is based on a learning curve Act_L which can be adapted to a specific worker. An actor has also a qualification according the usage of a specific tool, Act_E. This relationship is presented in the meta model – permission for the use of a *resource* (partial model of *resources*). During the course of a project two statuses can be assigned to an actor *Act*:

Act_{Status} = Actor status, where $Act_{Status} = \{Act_{Wait}, Act_{Work}\}$ depends on whether the actor is currently executing an activity (status Act_{Work}) or if he/she is waiting for the assignment of a task (status Act_{Wait}). The assignment process of a task is described in [Section 3.3].

3.1.4 Partial Model of Resources

For the execution process of a task (activity) tools and facilities (*resources R*) can be assigned. A resource can provide several functions and technologies for solving a task. This is described by mandatory (fixed) as well as variable attributes:

R_{fixed} = {ID, name, function / technology, organizational unit, required qualification of actor}

R_{var} = {assigned tasks/activities}

Tools and facilities used for the execution of an activity are designated with the necessary capacity and functionality. Additionally, each resource is explicitly assigned to an organizational unit (*OU*) and is described by the multiplicity of the attributes:

- $= 1$: ID; Name; organizational unit (resource is assigned to)
- ≥ 0: Formal qualification Act_Q or competence Act_C for using the resource
- ≥ 1: Function or technology

During a project a status of a resource is described by $R_{Status} = \{R_{Wait}, R_{Work}\}$ analogue to the model of the actor.

3.1.5 Partial Model of Work Object

Each activity possesses at least one input object and produces at least one output object. These input and output objects represent *Work Objects* (*WO*) like information elements or parts of the project and are not further specified. *WO* can be generated and be used for solving a task during an activity execution.

3.1.6 Input-Output Relation

The input-output relation specifies which output objects will be created depending on the input objects of an activity (work objects, resources and assigned actors) – necessary is at least one input and one output object for each activity. The output objects within the project characterize the course of a project, i.e., they represent the project's value-added process. To quantify the effort/makespan of an activity, the input-output-relation includes the attributes *expected effort* and *actual effort*. Thereby the effort, expected by the project manager, describes the duration for an activity. The value of the expected effort is based on the minimum number of actors necessary for the task and their "normal" performance. The calculation of the makespan of an activity is described in [Section 3.3].

3.2 Project Modeling

The C3 modeling method for weakly structured and domain-spanning development processes was developed based on the Unified Modeling Language (UML) and the identified requirements of Project Engineering [Killich, 99]. It was conceptualized especially for the recording and presentation of weakly structured cooperative work processes and has been successfully used for several years in research and industrial projects. The term "C3" is derived from the initial letters in the words cooperation, coordination and communication – the core elements of distributed work processes. The participative modeling of a project takes place in moderated workshops in which the project planners, alongside experts of the involved disciplines, identify tasks, personnel capacities, qualifications, resources and objectives of planning. The result is a semi-formal project plan that shows the contextual relationships between tasks, yet only indicates exact predecessor constraints where it is truly necessary. All other temporal relationships, e.g., the assignment of actors, facilities and resources to tasks, are based on the current availability and the achieved intermediate results during the simulated progression of a project.

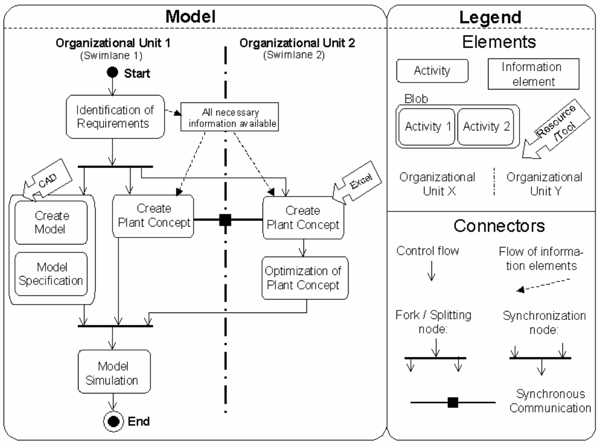

Figure 3: C3 model

The C3 method consists of 14 elements. [Fig. 3] shows the core elements in a short section of a chemical facility development. The so-called "blob" contains at least two activities without predecessor constraints. The connection between elements is specified by the following connectors:

- Control flow: Describes the connection between tasks/activities and the appropriated actors, facilities and tools.
- Flow of information elements: The flow of information elements describes the emitter, the receiver and the type of information.
- Synchronous communication: A characteristic of the synchronous communication is that all involved actors and resources must be available at the same time. If not, the synchronous communication cannot take place.
- Splitting node / Synchronization node: The splitting node splits information. Therefore, a parallel execution of activities is possible. The synchronization node merges parallel activities.

3.3 Procedure of Organizational Simulation

For the formal representation and implementation of the meta model timed stochastic Colored Petri nets are used [Petri, 62]. Therefore a project organization is mapped to a directed graph with places, transitions, arcs and markings. A great advantage of this approach is that a stepwise simulation of a Petri net can show weak points within the project organization.

The implementation of the activity-oriented simulation approach is carried out with the help of the java-based high-level Petri net simulator Renew, which was developed at the Department of Computer Science at the University of Hamburg [Kummer, 06]. The open-source code simulator Renew was chosen based on its graphical representation. In addition, the functionality related to the integration of sub-nets allows an exact representation of the development projects' hierarchical structure. The simulation tool was modularly constructed to attain the optimization of the project structure, as well as various – often contradictory – parameters [Tackenberg et al. 2008]. The separation of the *Task Net* and *Partial Models* ensures that the generation of various project scenarios (variation of the parameter configuration) is possible without the modification of the *Task Net* (description of activities and predecessor constraints).

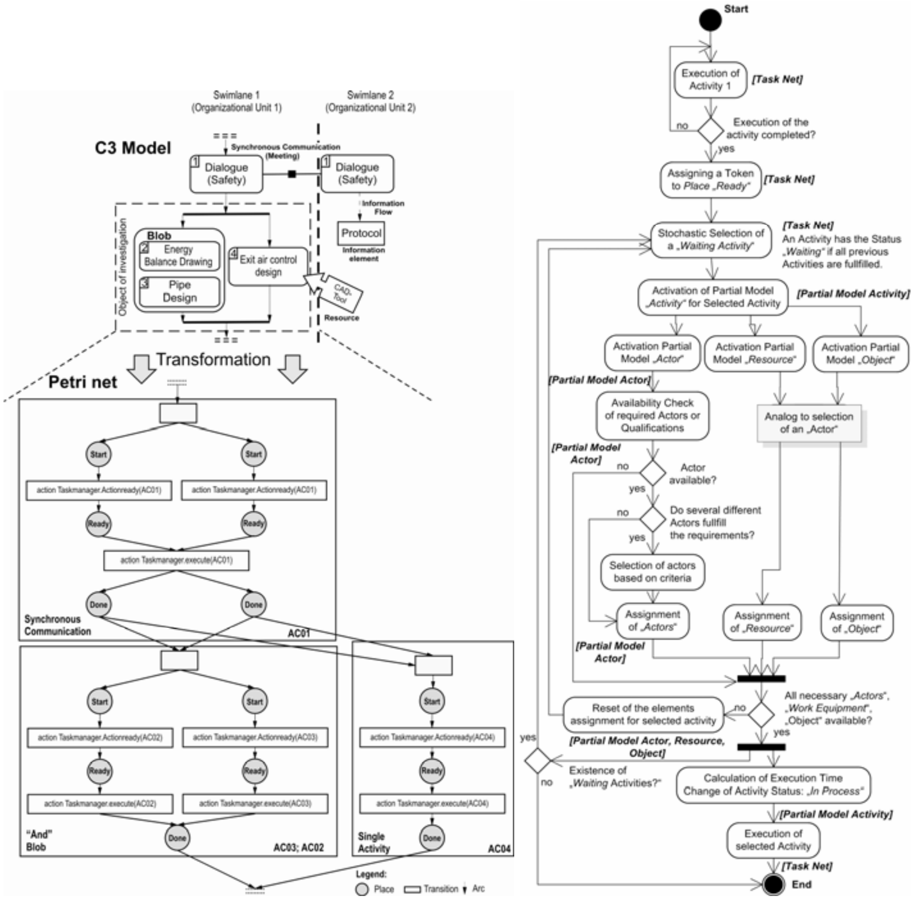

Figure 4: C3 model, Task Net (Petri net) and flow diagram

[Fig. 4] describes the significant functions and sequences of the simulation model in the form of a flow chart. The execution of activities of the development project under consideration is difficult to determine a priori due to the dynamic, creative and weakly structured work flow. This leads to deterministic as well as non-deterministic relationships in the simulation model.

Once "*Activity AC01*" of the *Task Net* is completed, a token is generated in the place "*Done*" of the activity [Fig. 4]. The generated token is directly transported to a transition that connects the places of the activities following "*Activity AC01*". Therefore, each "*Start*" place of the activities (No. 2, 3 and 4) receives a token that is transferred to the corresponding transitions of the activities. As a result, the *Partial Models of Actor*, *Resource* and *Object* – implemented as Java functions – are called up by one of the three transitions of the considered activities (No. 2 or 3 or 4). The probability of selecting one of the three transitions is uniformly distributed. As a result, the partial models of *Actor*, *Resource* and *Object* are called up from the *Partial Model "Activity"*. For the selected activity, the demands of actors and resources are compared regarding availability. If, for example, all required actors are available, a token for actors is generated at the place "*Ready*" [Fig. 4].

Only once all required actors, resources and objects have been placed (three tokens in place "*Ready*") can the execution of the *Partial Model Activity* begin anew. The execution time for an activity is calculated through invocation of the Java function "*Calculation of the effort*". This value is based on the given basic duration of the activity – supplied by the project planner – and the probability distribution of the expected processing duration (normal, beta or triangular distribution). If the basic conditions for the execution of the activity have been carried out, a token representing the execution process of an activity is sent to the transition. The token is located in the transition for the calculated processing time. After termination, the transition fires and a token occurs in the place "*Ready*". As mentioned in the flow chart, the simulation tool tries to simultaneously execute all waiting activities – given that predecessor activities have been fulfilled. The possible combinations of activities with regard to chronological order drastically increase the complexity and uncertainty of the project. Thus, the partially stochastic allocation of resources to activities, due to the "competition" for these, has a direct effect on the project structure and performance. A combination is randomly chosen per simulation run under consideration of the availability of actors and resources. This makes a comparison of the different project structure characteristics possible. The probability of a combination type and the time of execution for an individual activity are determined by the parameter constellation. For this purpose, the *Task Net* assigns the same probability of occurrence to all simultaneously executable activities (unless noted differently in the process editor) and attempts to carry out as many activities as possible in parallel through the immediate firing of transitions. In order to identify an optimal project structure for a given project configuration, the simulation run must be carried out repeatedly. The non-deterministic behavior of activities and their interaction leads to a widely spread course and performance of a project.

4 Case Study

The example project presented here refers to a completed development project in a large enterprise in the German chemical industry that was participatively modeled and simulated with the responsible project planners and leaders. The project comprises the design and calculation of a facility for a specific chemical process. Validation of the C3 method and of the entire simulation environment means proving that a project plan meets the goals that have been specified a priori. Thus, before a project model can be used to identify causes and effects, it is necessary to check whether the interrelations are valid representations of the system.

4.1 Project Structure

For the structural validation of the simulation model, the adjustment of the numerous parameters is particularly critical. These parameters – introduced in [see Section 3.1] – include the number and competence of actors, the quantity and functionality of the resources, the moments of the probability distribution of the activity durations, the probability of occurrence of certain activities, and many others. The values of these parameters, which were generated during several workshops with company project planners, result in complex system dynamics. In the project, the company-internal experts as well as the client and the supplier determine the structure and the configuration of the project. The project consists of 62 activities with a many abstract sequences of execution and undetermined assignment of actors and resources [Fig. 5]. The effects of the execution sequence of tasks 6 to 11 in "*Blob 1*" as well as the assignment of actors to these activities regarding project performance were of particular interest. However, throughout the course of the project, different project performances can occur due to the blobs (2 to 7) and the branches in the project structure. To investigate this effect, the relationship between the total duration of the project and the number of actors, tools and facilities involved was analyzed.

The number of actors was varied systematically, starting with the smallest possible number and was then expanded by a stepwise addition of actors with different qualification profiles. In a second phase, the resources (laboratories, laboratory equipment, etc.) necessary for project processing were varied with regard to number and functionality. The fact that different experts named different times when expected durations for single activities were collected in a workshop led to a scattering of the actual possible effort for the execution of an activity. In the simulation runs, those relative scatter diagrams varied between ±10% and ±30% from the mean. However, a normal distribution within these boundaries cannot be presumed, since experience shows that activities tend to require a larger effort than expected. Instead, it should be assumed that the majority of efforts lie above the estimated mean. This results in a β-distribution in the simulation. Here, the estimated efforts of single activities differ in the chosen shape parameters α and β of the β-distribution. These "virtual count" parameters for determining time consumption lead to a significant variance in project duration when a simulation run for each project constellation (specific combination of actors and resources) is executed several times.

4.2 Hypothesis

The following two null hypotheses were formulated for a comparative assessment of the simulation results relating to the actors of projects in the chemical industry:

- H_{01}: The dependent variable "*Total Time of Project Duration*" (TT_{PD}) is not influenced by the independent variable "*Number of Actors*" involved in the project (N_{Act}).
- H_{02}: The dependent variable "*Total Time of Project Duration*" (TT_{PD}) is not influenced by the independent variable "*Quantity of Resources*" (N_R)

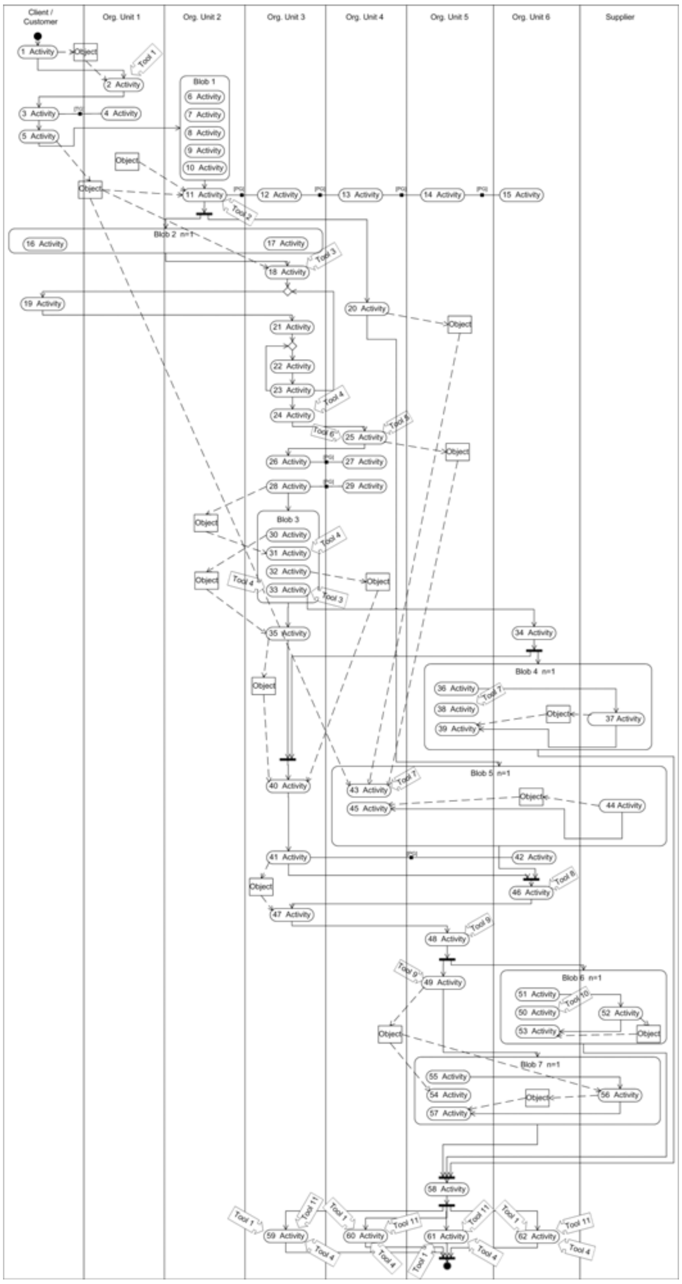

Figure 5: C3 model of a development project

4.3 Simulation Results and Interpretation

The “project performance landscape” [Fig. 6], developed from the means of the single simulation runs for each project constellation, illustrates the effects of a systematic variation of the independent variables on the simulated project durations of both development projects. The simulation and analysis of the different compositions of a project team show that with an assignment of three actors, the total duration stays nearly constant, independent of resource quantity. Graphically, this phenomenon is represented by “Plane 1” [Fig. 6]. For the project under investigation here, the reduction of the project duration depends mainly on the number of actors involved. However, the number of actors is not the only determining factor. Thus, for this development project, the influence of actor-specific qualifications – process engineer (VT) and facility technician (AT) – on project duration were investigated. The analysis of the simulation data provided evidence that the qualification of the fourth or fifth actor directly influenced project duration. The involvement of a sixth actor, on the other hand, resulted in an increase in project duration, which a detailed analysis of the project runs suggests is due to the higher coordination efforts required and an unsuitable qualification profile of the actor concerned.

Interpretation of the simulation results for the development project shows that with a constant basic endowment of 11 tools, the project duration can be lowered by 18% (from 314.1 Time Units [TU] to 255.2 TU) exclusively through the assignment of additional actors (with the characteristics of Actor 4 - VT), (Actor 5 - AT). In addition, if the number of available tools and facilities (resources) is increased up to 23 tools, a reduction of 5% (242.65 TU) can be achieved compared to the basic endowment (11 tools) [Tab. 1]. Overall, the simulation suggests that a reduction of the original project duration from 314.1 TU to 234 TU, approximately 25%, can be achieved.

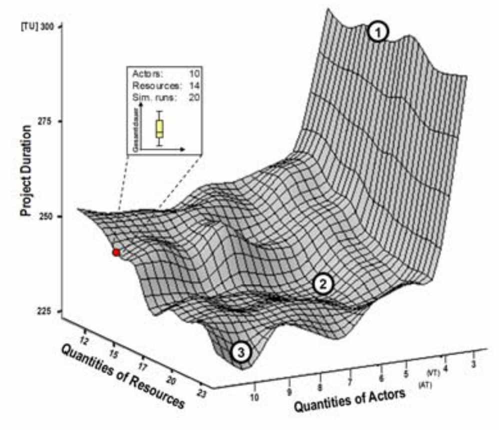

Figure 6: Predicted project durations dependent on project configurations

If the project planner’s objective is to minimize project duration, the project constellation in which the global minimum is achieved must be identified. Identification of a local minimum on level 2 gives the project planner concrete instructions on how to minimize project duration by integrating additional employees that have the characteristics of Actor 4 (VT) and Actor 7 (representing an AT), as well as by adding a tool of type 15. The global optimum (plane 3) can be achieved by the maximum quantity of actors (10) and resources (23) [Tab. 1]. In comparison to level plane 2, the global optimum offers an additional reduction of the project duration by 3.4%. On the basis of the "project performance landscape" the project planner has to decide if the expense for the additional actors and resources justifies the shorter project duration.

		TT_{PD}			
N_{Act}	Test runs	Mean (in [TU])	Std. Deviation (in [TU])	Delta	%
Actor 3	25	312.80	12.76	-	
Actor 4	25	274.76	12.53	-38.04	**-12.16**
(VT) 4	25	274.64	13.71	-0.12	-0.04
(AT) 4	20	264.10	8.45	-10.54	-3.84
Actor 5	25	270.08	10.56	5.98	2.26
(AT) 5	20	242.65	13.94	-27.43	**-10.16**
Actor 6	25	274.32	13.07	31.67	13.05
Actor 7	25	252.56	13.73	-21.76	**-7.93**
Actor 8	25	247.48	9.37	-5.08	-2.01
Actor 9	25	244.84	10.63	-2.64	-1.07
Actor 10	25	234.16	11.21	-10.68	-4.36
Total	265	263.31	24.29		

Table 1: Sensitivity of dependent variable TT_{PD} with 23 resources regarding variation

In this example, a reduction of the project duration can be predicted in very early planning phases through the verification and evaluation of different project constellations and the corresponding identification of important relationships between actors, specific resources and project duration.

		TT_{PD}			
N_R	Sim. runs N	Mean (in [TU])	Std. Deviation (in [TU])	Delta	%
11	25	251.80	11.45	-	-
12	25	252.96	11.61	1.16	0.46
13	25	259.20	11.50	6.24	2.47
14	25	251.24	16.27	-7.96	-3.07
15	25	249.20	10.71	-2.04	-0.81
16	25	252.28	12.07	3.08	1.24
17	26	242.96	16.56	-9.32	-3.69
18	25	238.72	13.69	-4.24	-1.75
19	25	242.76	11.40	4.04	1.69
20	25	240.56	15.77	-2.20	-0.91
21	25	242.40	15.39	1.84	0.76
22	25	237.20	10.86	-5.20	-2.15
23	25	234.16	11.21	-3.04	-1.28
Total	326	245.79	14.76		

Table 2: Sensitivity of dependent variable TT_{PD} with 10 actors

Regarding the evaluation, it has to be considered that there is a mean total amount of work (sum of the amount of work of all activities in the project) over all simulation runs. The variation of the project duration TT_{PD} can therefore be assumed to be a result of the different project configurations (actor and resource assignment to tasks or activities). In this context, it is of interest for project planners that the modification of the quantity and characteristic of different resources N_R by the maximum quantity of actors (10) reduces the project duration TT_{PD} by just 7%. Compared to the variation produced by differing numbers of actors this indicates a clearly lower impact of resources on project performance. Due to the simulation results of the presented case study the hypotheses H_{01} and H_{02} above have to be rejected.

5 Conclusions and Future Work

The concept of an organizational simulation model for complex development projects in industry founded on the C3 modeling language offers project planners a suitable technique for quantitative comparisons of alternative project organizations at an early planning stage. The project model consists of five constituent models. It thus allows project planners to design, study and optimize the project structure, project configurations and the project performance effectively. As unscheduled events (e.g. modification of the chemical process due to modified product specifications, insolvency of a supplier etc.) can occur during the course of a project, this approach allows simulation studies to be applied in order to validate project planning both before and during the project. Furthermore, the simulation model offers a graphical representation of the process due to its close connection to the C3 modeling language and the Renew simulation environment.

The experiments with the simulator produced valid results, as confirmed by the experts of various leading German chemical engineering companies. A further evaluation of the effectiveness and efficiency of the proposed approach is difficult due to the high practical relevance of the approach. A comprehensive validation of existing simulation approaches in industry is not known by the authors and is difficult to implement. For such a validation two identical projects have to be set up at the same time. One project has to be managed by the use of a simulation model whereas the control project is managed based on the knowledge of project managers supported by Computer Supported Cooperative Work (CSCW) approaches [Simone, 97], knowledge management concepts [Won, 03] or conventional software solutions, e.g. Microsoft project. Such an experimental setting in an enterprise cannot be achieved due to the required complexity and therefore project budget. Therefore an experimental benchmarking of simulation based generated project organizations in comparison to project plans designed by project managers were done by the group of Levitt [KHosraviani, 05]. A similar experimental setting representing the main aspects of development projects in the chemical industry is designed by us and will be implemented in near future. However it could be shown that in average the project plans generated by the simulation model are more effective regarding the project duration and the parallel execution of activities than the observed project plans of the chemical industry.

Acknowledgements

The research was funded by the German Research Foundation according to the transfer project TB61. We would like to thank the Bayer MaterialScience AG as well as InfraServ GmbH & Co. Knapsack KG for their excellent cooperation.

References

[Biegler, 99] Biegler, L.T., Grossmann, I.E., Westerberg, A.W.: “Systematic Methods of Chemical Process Design“; Prentice Hall PTR, New Jersey (1999)

[Cho, 05] Cho, S.-H., Eppinger, D.: “A Simulation-Based Process Model for Managing Complex Design Projects”; IEEE Transactions on Engineering Management, 52, August (2005), 316–328.

[Cohen, 92] Cohen, G. P.: “The Virtual Design Team: An object-oriented model of information sharing in project teams”; Ph.D. Dissertation, Department of Civil Engineering, Stanford University, Stanford, CA, (1992)

[Eppinger, 94] Eppinger, D., Whitney, D. E, Smith, R. P., Gebala, D. A.: “A model-based method for organizing tasks in product development”; Research in Engineering Design, (1994)

[Foltz, 08] Foltz, C., Schneider, N., Kausch, B., Wolf, M., Schlick, C. M., Luczak, H.: “Usability Engineering”; In: Collaborative and Distributed Chemical Engineering, Nagl, M., Marquardt, W. (Ed.); Springer, Berlin / Heidelberg (2008), 527-554.

[Huberman, 05] Huberman, B.A., Wilkinson, D.M.: “Performance Variability and Project Dynamics”; Computational & Mathematical Organization Theory, 11, 4 (2005), 307-332.

[Kausch, 08] Kausch, B., Schneider, N., Tackenberg, S., Schlick, C.M, Luczak. H.: “Integrative Simulation of Work Processes”; Collaborative and Distributed Chemical Engineering Editor: Nagl, M., Marquardt, W., Springer, Berlin Heidelberg, (2008) 1037-1076.

[KHosraviani, 05] KHosraviani, B.: “An Evolutionary Approach for Project Organization Design: Producing Human Competitive Results Using Genetic Programming”; Doctoral Dissertation, Department of Civil and Environmental Engineering, Stanford (2005)

[Killich, 99] Killich, S., Luczak, H., Schlick, C.M., Weissenbach, M., Wiedenmaier, S., Ziegler, J.: “Task modelling for cooperative work”; Behaviour & Information Technology, 18, 5 (1999), 325-338.

[Kim, 03] Kim, J., Wilemon, D.: “Sources and assessment of complexity in NPD projects”; R&D Management, 33 (2003), 15-30.

[Krause, 04] Krause, F.-L., Kind, C., Voigtsberger, J.: “Adaptive modeling and simulation of product development processes”; CIRP, STC, (2004), 135-138.

[Kummer, 06] Kummer, O., Wienberg, F., Duvigneau, M.: “Renew – the Reference Net Workshop”; (2006), also appeared as electronic version, http://www.renew.de/.

[Levitt, 99] Levitt, R.E., Thomsen, J., Christiansen, T.R., Kunz, J.C., Jin, Y. and Nass, C.: “Simulating project work processes and organizations: Toward a micro-contingency theory of organizational design”; Management Science, 45, 11, (1999), 1479–1495.

[Licht, 07] Licht, T., Schmidt, L., Schlick, C., Dohmen, L., Luczak, H.: “Person-Centered Simulation of Product Development Processes”; International Journal Simulation and Process Modelling, (2007), 204-218.

[Lukas, 07] Lukas, M., Gärtner, T., Rohleder, N., Schlick, C.: “A Simulation Model to Predict Impacts of Process Alterations”; Proceedings of the 9th DSM Conference, Munic, (2007), 127-136.

[Mahesh, 07] Mahesh, M., Ong, S.K., Nee, A.Y.C., Fuh J.Y.H., Zhang Y.F.: “Towards a generic distributed and collaborative digital manufacturing”; Robotics and Computer-Intergrated Manufacturing, 23 (2007), 267-275.

[Osborne, 93] Osborne, S.M.: “Product Development Cycle Time Characterization Through Modeling of Process Iteration”; Master’s Thesis (Mgmt./Eng.), M.I.T., Cambridge, MA, 1993

[Petri, 62] Petri, K.A.: “Kommunikation mit Automaten / Karl Adam Petri”; Universität Bonn, Bonn (1962)

[Raupach, 99] Raupach, H.-C.: “Simulation von Produktentwicklungsprozessen”; Dissertation, TU Berlin, Berlin, (1999)

[Savarimuthu , 04] Savarimuthu, B. T. R., Pruvis M., Fleurke, M.: “Monitoring and controlling of a multi – agent based workflow system”; ACM International Conference Proceeding Series, 54, Dunedin, New Zealand, (2004), 127-132.

[Schlick, 07] Schlick, C. M.: “Grundlagen dynamischer Geschäftssysteme“; Skript Arbeitswissenschaft IV, Business Dynamics; Institut für Arbeitswissenschaft der RWTH Aachen, Aachen (2007)

[Schlick, 08] Schlick, C., Beutner, E., Duckwitz, S., Licht, T.: “A Complexity Measure for New Product Development Projects”, Proc. IEMC 2007, IEEE Publishing, Austin, Texas, USA, (2007), 143-150.

[Simone, 97] Simone, C., Divitini, M.: “Ariadne: Supporting Coordination through a Flexible Use of the Knowledge on Work Processes”; J.UCS (Journal for Universal Computer Science), 14, 19 (1997), 865-898

[Steward, 81] Steward, D.V.: “The design structure system: A method for managing the design of complex systems”; IEEE Transactions on Engineering Management, 8, (1981), 71–74.

[Tackenberg, 08] Tackenberg, S., Kausch, B., Malabakan, A., Schlick, C. M.: “Organizational Simulation of Complex Process Engineering Projects in the Chemical Industry”; Proc. CSCWD 2008, IEEE Press, Xi’an, China (2008), 648-653.

[Tian, 04] Tian, F., Li, R. and Zhang, J.: “Modeling and analysis of collaborative design activities using Fuzzy-timing high-level Petri Nets”; Journal of Computer Aided Design & Computer Graphics, 16, 3, (2004), 267-274.

[VDI, 01] VDI-direction VDI 3633: “Simulation von Logistik-, Materialfluss und. Produktionssystemen”; December (2001)

[Won, 03] Won, M.; Pipek, V.: “Sharing Knowledge on Knowledge – The eXact Peripheral Expertise Awareness System” J.UCS (Journal for Universal Computer Science), 9, 12 (2003), 1388-1397

[Yao, 06] Yao, Y., Fan, W., Xiong, L.: “Research on complex product development process simulation and its optimization”; Journal of System Simulation, 18, 3, (2006), 726-730.