An Integrative Simulation Model for Project Management in Chemical Process Engineering

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ABSTRACT

The planning of development projects significantly influences the costs created by the projects as well as the success of the development projects. The presented approach shows a method for the modeling and simulation of development projects in process engineering based on Petri net simulation. The simulation of an example process displays the connections between different influencing parameters such as team configuration, the availability of needed tools, the variance in processing times, and the qualification of the persons involved. It could hereby be determined with which parameter combination and with which amount of employed staff the shortest development time can be attained. In the outlook several additional parameters are named that are prepared and will be added to in the further research project in order to make further detailed analyses possible.

INTRODUCTION

Only 13% of work in projects in Germany are actually value-adding, out of which a total loss of value of approximately 150 billion Euros results (Gröger 2006). Reasons for these deficits are bad decisions in the selection of projects, yet also the insufficient defining of goals. While these problems affect the project environment in the business there is also another area that affects the project structure. This area covers the development and continued use of findings and information in projects. This, along with the accurate implementation of employee competence and availability, must be improved through workflow planning. These problems are well-known in process engineering as well. The project correlations in the process development were analyzed in the Collaborative Research Center (CRC) 476. Besides these theoretical results eight out of 12 project managers from the field of process engineering that were surveyed said that a lack of coordination and poor information flow were the main causes for sub-optimal project efficiency. Support tools were developed that improve the cooperation of the various development areas and that are meant to reduce the interface-related losses. A simulation system identifies the necessary correlations and information flows between the organizational units involved based on a semi-formal project model. The simulation clarifies the connection between the assigned resources and persons, thereby making the identification of the project duration possible through defined input of resources or vice versa. As a result, the project planner has the possibility to analyze different workflow management structures and then plan the input of resources or the resource-relevant project structure accordingly.

DEVELOPMENT PROJECT IN PROCESS ENGINEERING

An example project was recorded that reproduces typical workflows of process engineering to take into consideration the current requirements within process engineering alongside the procedure models described in literature. The development of the synthetic material Polyamide 6 (PA6), which is usually used in the manufacturing of textiles, yet also as friction and heat resistant construction material, represents the characteristics of process engineering development processes.

Process development usually begins with literature research that serves the purpose of information collection, and which is frequently repeated in the development project. Based on the collected information, yet also based on the experience of the developers involved, the decision for the batch or the continuous operation is made. This decision influences the additional procedure-dependent development steps. In the case of our example, the development of the PA6 process was performed in cooperation with chemical engineering companies, the developments of the reaction, separation and extrusion follow. These developments result individually, yet depend heavily on each other, founding the basis of the complexity within the development projects of chemical engineering. The development of the facility area necessary for the various steps is based on the representation of the mathematical, chemical and physical correlations. Consequently, the main task in here is the creation and analysis as well as the improvement of these models. To conclude, the final decision regarding the plant concept is made based on the simulation results of previous work steps.

Definition of the Simulation Approach

A workflow simulation model of development projects in the chemical industry was developed at our institute in recent years. One way to differentiate simulation models is by the level of detail found in human modeling. VDI-Guideline 3633 distinguishes between person-integrated models (person as reactive action model) and person-oriented models (display of various additional traits possessed by person) (VDI-Guideline 1993, Zülch 2004). Furthermore, simulation models of product development processes can, similar to VDI-Guideline 3633, be differentiated by two forms of model logic:

1. In the case of actor-oriented simulation models, system dynamics are produced by actors (modeled persons or organizational units) based on specific task (Steidel 1994, Christiansen 1993, Cohen 1992, Jin and Levitt 1996, Levitt et al. 1999, Licht et al. 2004).

2. In process-oriented simulation models system dynamics are produced by activities through the usage of resources (persons, tools) (Browning et al. 2000, Cho et al. 2001, Cho et al 2005, Gil et al. 2001, Raupach 1999).

According to this terminology, the workflow simulation model in process engineering that will be presented here can be characterized as a person-oriented and process-oriented approach.

EXISTING SIMULATION APPROACHES

In the field of process and product development processes only a few adequate simulation techniques are well established.

The so-called Virtual Design Team (VDT) is an actor-oriented model especially designed for the simulation of product development projects which was created by Levitt's research group at Stanford University. Early versions of the VDT were already able to model actors and tasks, as well as the information flow between these two instances (Christiansen 1993, Cohen 1992). Subsequent versions then also took into consideration the different goals of actors, the construction of exceptions, and in addition, exception handling (Jin et al. 1996, Levitt et al. 1994, Levitt 1999). A process engineering context is not considered in this model, and participative creation of the simulation model or optimization of workflow management will not be supported through the methodology.

Independent of Levitt's group, Steidel managed to develop a further actor-oriented simulation model for product development processes (Steidel 1994). This model also ignores particularities of process engineering. Likewise, participative creation of the simulation model or optimization of workflow management will also not be supported through the methodology.

Raupach formulated a process-oriented approach for the simulation of product development processes so that consistency can be observed in various construction solutions. The product structure is accounted for in great detail through this approach (Raupach 1999). This fact makes it hard to apply in contents with inherent variability e.g. the process engineering context, participative process creation, and optimization of workflow management. Those points are not addressed. Interdependencies between project success criteria and factors influenceable by technical planning will not be examined in this approach.

Eppinger's research group at the Massachusetts Institute of Technology developed numerous process-oriented simulation models (Browning and Eppinger 2000, Cho and Eppinger 2001, Cho and Eppinger 2005).

Browning's simulation model assumes that an unlimited supply of resources (in this case, employees) exists, meaning the simulation results of this model are limited in their representation of reality. Cho's simulation model does take note of the limitation of resources available in a product development project, yet a corresponding processing of multiple activities is also not possible in this case. An organizational connection to process engineering is non-existent, and participative process creation or an optimization of workflow management is not intended. Interdependencies between project success criteria and factors influenceable by technical planning will hardly be considered.

A process-oriented model for the simulation of a factory-planning project was developed by a research group headed by Tommelein at the University of California at Berkeley (Gil et al. 2001). This model observes the effects of altered requirements on the planning process and the project length of construction projects. Particularly, examination of so-called postponement-strategies occurs, in which the start of a succeeding operation is purposely delayed in order to increase the quality of the work results of the preceding-operation. Similarly, the simulation model assumes an unlimited supply of resources. However, in a process engineering context, participative process creation or an optimization of workflow management is not dealt with. Interdependencies between the technical planning of influenceable factors and project success criteria are not sufficiently taken into consideration in this model.

The person-centered simulation model of Licht (Licht et. al. 2004) offers an, according to our requirements, more suitable approach to analyzing development processes of products and processes. The model includes many different process specific aspects of the process, such as type and complexity of products, characteristics of the employees, tools, organizational structure, etc. Due to the person-oriented approach, the model also serves as a realistic method for employee management by providing employees' behavior. The negative consequence, however, is that the model is very complex and therefore difficult to apply.

INTEGRATIVE SIMULATION MODEL

The simulation model presented here offers a suitable technique for project planners in order to compare several alternative ways of project organization at an early stage, with respect to the number of persons, tools, time and other resources involved.

With its close connection to the easy to understand and semi-formal modeling language C3 (Killich et al. 1999), designed at our institute, the model enables a transparent and very concise, understandable and well applicable representation, making it easy for the user to understand and to work with the simulation model. The goal of this simulation model is to combine the advantages of C3 (Eggersmann et al. 2001, Schneider et al. 2006) and the advantages of the simulation, that is to say, the possibility of planning, analyzing and rearranging the development process based on mathematical constraints. In addition, the model used offers the chance to optimize the development process with respect to the development duration as well as in consideration of resources and the development costs.

The entire simulation model is based on the following five partial models:

1.) the task network, 2.) the task, 3.) the employee, 4.) the work tool, and 5.) the information, which will be examined in greater detail in the following.

Task Network Model

The development of a new or modified chemical process usually takes place in team spanning development projects. It is in these projects that the complexity concerning the organizational structure as well as the workflows should be reduced. The model concept of the task network describes the workflow management of the development project. In addition, the individual phases of the development process will be divided into work tasks through the use of a workflow plan (a so-called task network). Predecessor-successor-relationships, i.e., the logical order of execution - for example, due to causal relationships between individual underlying activities - of the tasks will be laid down in the task network. Hereby it is determined, for example, that the literature research precedes the additional analysis. The workflow plan is primarily participatively recorded and displayed through the C3 modeling language. The work tasks of the task network are assigned to organizational units for execution. Apart from the chronological sequence of tasks, the assignment of work equipment for the associated tasks is also displayed in the task network. An overview of the PA6 development process, described earlier, with 79 tasks is schematically displayed in Figure 1.

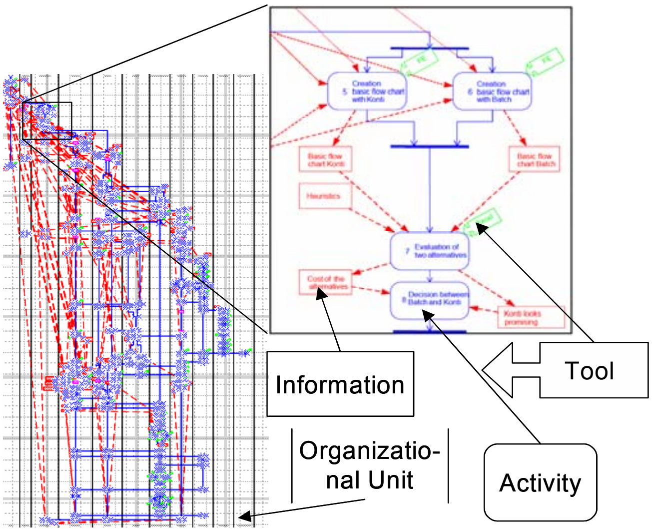

Figure 1: Schematic illustration of the PA6 development Process including a detailed view of some basic C3 elements

Additionally in the extract on the upper right a detailed view into the process is given, where the main elements of C3 are marked and briefly explained. A software environment, especially designed in the research project to support recording and visualization of work processes with the C3 method, supports the recording process as well as the visualization and software based transformation of the working process structure. In Schneider et al. (2003) this software environment for work process modeling is described in more detail.

Task Model

The task network consists of the tasks in the development process that need to be worked on. The processing of each individual task is described in detail in this model concept. Within the tasks there is information about the subject matter needing to be processed, a necessary work tool, a profile of possible persons to do this processing, input and output information of the task as well as the expected duration needed to process the task. For the processing of a task, a qualified person and, if necessary, adequate tools are selected to achieve the goal of only implementing the most qualified employee actually available for the handling of the task. Each person is then also assigned a value that reflects the quality of the person, dependent on the task at hand and the required tools to complete the task. This value is calculated from the weighted sum of the person’s assigned characteristics (cp. Model Concept of the Employee).

The weighting and the different attributes are not constant and can be varied depending on the area of application. The most highly qualified person will then take on the task, though it may occasionally be the case that the basic skills needed for a certain task are not possessed by anyone. In such an event, the task cannot be completed until someone suitable for the task becomes available. Only once the adequate labor and essential work tools are available the task can be carried out according to its duration, which depends on the underlying distribution function and the person employed for the task.

Employee Model

According to the person-oriented basic approach of simulation, the definition of the characteristics of employees and thus the participants in this model concept is of particular importance. At the same time, an attempt is made to model the person as realistically as possible. This entails displaying employees’ characteristics and abilities that have an influence on the allocation of persons to the various tasks as well as the task processing time and work quality of the different development process tasks. The described attributes of an employee are summarized in the following:

- Productivity of an Employee

Each person is assigned a numerical value that describes the individual productivity, i.e., output. This value improves the quality of the employee in the selection of the most qualified employee for a task, and also has an influence on the processing time of a task.

- Qualification in terms of a particular area of work

  The tasks of the development process are arranged into swim lanes in accordance with C3 modeling. These swim lanes describe the areas of work, for example, such as in the PA6 Processes case study in which the work areas of Simulation or Separation were described. The persons possess abilities and skills that qualify them for the processing of tasks in certain areas of work, yet then also make them unsuitable for others.

- Ability to deal with particular work tool

  Several tasks require a work tool such as a software tool or a machine for their processing. The persons possess abilities and qualifications that describe how well they can handle certain work tools. This means a person must not only bear the appropriate qualifications to complete the task, but they must also have the ability to carry out the task through use of the necessary work tools.

- Learning aptitude

  An employee begins his career with certain basic qualifications, i.e. abilities that were acquired during schooling, or inherent characteristics. During the course of a career, however, a person's abilities can change. Due to routine tasks and new methods and expertise, certain qualifications can actually be improved. Alternatively, abilities not put to use over a greater period of time can also be weakened. This capacity to learn and unlearn is shown in a simulation model through a learning curve that is attributed to each person. A more detailed description of the learning curve will be presented later on.

Personal qualifications and abilities are taken into account in the model concept in terms of recognizing that each person is able to act out a variety of activities. This portfolio of possible activities can be directed at specific job descriptions that are representative of the different organizational units and work means related to the process.

Work Tool Model

The influence of work tools on the completion of tasks in the scope of the execution of activities through an employee is held in the partial model of work tools. The allocation of work tools to tasks results through the work organization of the development project. Simultaneously, the information of which work tools can be used for which task is already retained in the model of the task network. Due to their scarcity, work tools must be reserved prior to their use. Also, a tool can be used by only one employee at a time, though more than one tool can be used for a specific task. The amount of possible work tools cannot be exhaustively declared since the amount of possible tasks in need of completion, detached from individual case examples, cannot be fully indicated. Thus, similar to the task network and the work organization in relation to the development project that is to be simulated, the list of work tools must be created and must be specific. The level of detail is also to be specified individually for each case. This means that it may be enough in a project to simply differentiate between work tools for the creation of technical drawings between drawing board and CAD; in other projects, due to the use of varying computing systems and thereby related file formats, there must be distinction between different computing systems.

Information Model

Information should be viewed in the same light as work tools. Information is already assigned to tasks in the task network and has an influence on the duration of the development project. Information can be grouped into input and output information. Input information describes files or documents that are necessary for the processing of a task. The processing of a task cannot start without this information.

For example, for task seven of the case example (cp. Figure 1), evaluation of two alternatives for the creation of a basic flow chart with Batch or Konti requires information about various heuristics as well as output from the basic flow charts of Batch and Konti. These can either be produced in the form of output information through a different task, such as the Batch or Konti information which is linked to the previous tasks, or be made available outside of the analyzed workflow as in the case of the heuristics.

Through the processing of a task, output information is treated as its result. The results of a task, which may eventually be needed for the processing of later tasks, are described and are made available as input information.

IMPLEMENTATION OF THE SIMULATION MODEL

To show the implementation of the simulation model, the Polyamide 6 process (Eggersmann 2004) was used as an example case of the CRC. The underlying process here, consisting of 79 activities executed by the coordination between eight organizational units (separated by swim lanes in the C3 model), describes the different phases of new development for the manufacturing of PA6.

To maintain the distinctiveness of the C3 language the simulation model was implemented using a person-oriented and process-oriented approach. Also, to formally describe the simulation model, the notation of Timed Stochastic Colored Petri Nets was taken up. The development project was mapped into a directed graph consisting of places, transitions, arcs, and markings. A great advantage of this simulation notation is that a stepwise simulation can easily identify weak points. In this case, Petri Net tokens as representatives for active elements indicate the status of work progress, and indicate it as a result of possible weak points.

The simulation model was implemented using the Petri Net Simulator Renew (Kummer et al. 2004). Renew is a Java-based high-level Petri Net simulator developed at the Department of Informatics at the University of Hamburg. The simulation tool provides a flexible modeling approach based on reference nets as well as a user-friendly design by the use of a graphical presentation. Renew is a computer tool that supports the development and execution of object-oriented Petri Nets, which include net instances, synchronous channels, and seamless Java integration for easy modeling.

The entire Petri Net model according to the description of the Polyamide process is composed of different sub-networks that correspond to partial models that, for instance, represent the universal model. The implementation of this partial model in the form of sub-networks will be examined more closely in the following.

Task Network

The Task Network describes the workflow management of the development project. The predecessor-successor-relationships between individual tasks are defined in the corresponding Petri Net. Certain tasks are released for further processing through appropriate transitions in this network when all necessary predecessor tasks have been completed and the adequate persons as well as resources (work tools, input information) for the processing are available. A section of the task network of the PA6 Process is displayed in Figure 2. Based on the process-oriented approach, the task network builds the link between the partial models. Here are the rough correlations, such as how the development project implements workflow management and the necessary resources for the processing of individual tasks, whereby the exact processing of tasks are represented in the network of the task.

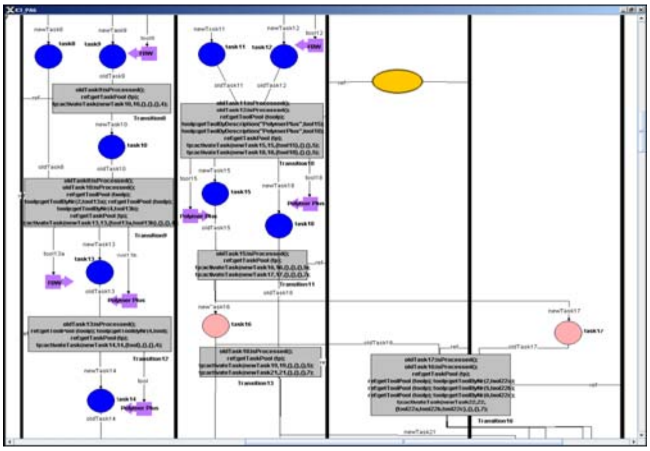

Figure 2: Screenshot of a section of the PA6 Process

Task

The net for the representation of the processing of a task builds the link between the partial model of the work tool and the employee. Here, the person who will process the task is chosen and the necessary resources are reserved.

In doing so, the basic conditions are directed at the person who is qualified for the processing of the task. These requirements are implemented in the respective task and organized according to the area of application, with the most qualified person executing the task. The qualification level (Q_L) is calculated as follows:

$$Q_L = \alpha P + \beta Q_w + \gamma Q_t$$

The weights α, β and γ determine how strong the influence of an attribute is on the quality level of a person. According to the model concept of the person, the attributes productivity P, qualification based on the field of work Q_w and the ability and qualification to handle a work tool Q_t are viewed as influencing variables. Moreover, the duration of a task is determined and thus processed in the network of the task. Effort and duration for the processing of a task depend on the estimated average processing duration as well as the qualification and proficiency level of the specific employee. The choice of work tools used along with the procurement of additional information can also have an effect on the duration and processing of a task. In order to realistically depict the processing time of a task, which can only be approximated, the aid of a probability distribution is employed. A normal distribution with relative variance between 10% and 30% of the mean was established for the first test runs of the simulation model.

The administration of the tasks of the workflow is implemented in the Task Pool. The Task Pool is a help network that, in combination with the Task Net, displays a task on the model concept. The various tasks are initialized and managed in the Task Pool.

Person

The employees involved in the project, inclusive of their characteristics and capabilities, are implemented in the Person Net. The management of employees is organized in an auxiliary net, the so-called Person Pool. Here, the current number of available persons as well as their current status - ”currently in processing” or ”free for the next available task” - is deposited. Before a task can be processed, however, a search occurs in the net for the fitting employee for the processing of the task. (cp. the Net of a Task).

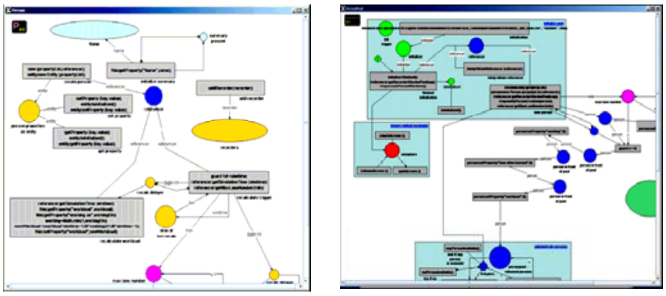

Figure 3: Screenshot of the Renew Person Net and the Person Pool

In Figure 3 a section of a screenshot of the Person Net as well as the Person Pool is mapped. Task-specific abilities of a person are improved, thereby increasing the attributes of that person when a task is processed. This learning ability of the employee is implemented through a learning curve as follows (figure 4):

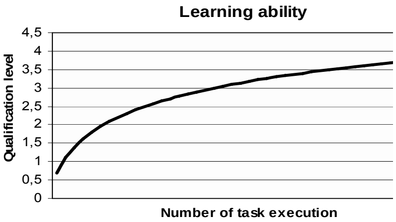

Figure 4: Coherence between individual Qualification and number of Task executions

In the implementation of the learning curve it was not possible to deal with the learning ability of every single employee, though a general function was implemented.

The Tool Net

The work tools available for the work process are administered in the Tool Net and the Tool Pool. In the model presented here, a name and a distinct identifier are sufficient as a characteristic of a work tool. Modeled on the Person Pool, the Tool Pool implements the maintenance of work tools, that is to say, the current number as well as status of available work tools is accounted for. It may sometimes be the case that another person is already using this specific tool, leading to waiting times.

Implementation of Additional Functions

A universal model composed of further help networks exists in addition to the networks that describe partial models. In this universal model functions, such as the initialization of the model or the output of simulation model results, are implemented. These act as links between the various nets.

The input data of the simulation model (the description of the tasks in the development project, including their demands of the employee as well as their necessary resources, the amount and attributes of the employees involved in the project, as well as the work tools available for the project) is organized in tables and can be viewed with the help of the initialization network.

Additional functions, for example, the calculation of the normal distribution of the processing time or the printout of simulation results, are implemented in independent Java classes whose functions are invoked and performed in corresponding parts of the network, more precisely, in the transitions.

RESULTS AND DISCUSSION

Concerning the structural validation of the simulation model, the coordination of the numerous individual parameters among each other should be seen as particularly critical. These parameters produce extremely complex system dynamics through which the investigation and evaluation of the models is in turn made more difficult.

In the first test runs of simulation the number of persons was varied and afterward set to the optimal number. Following this, the number of tools was also varied. The influence of these factors on the simulation time was then examined in order to judge the validity of the simulation model. To do so, the expected durations of the individual tasks were acquired in multiple expert workshops.

As described in the following, these initial test runs showed satisfactory behavior.

Examination of Dependence between Number of Employees and Total Project Duration

The relationship between the total duration of the development project and the number of organizational units working on them - in the present case identical to the persons working on the task - was analyzed in the first simulation runs. Also, it was assumed in the form of the simplest case, that only one person processed a task. For this comparison the amount of persons was varied between one and 11. The variance of the expected duration was still regarded as an independent variable and then changed in three steps, between 10%, 20% and 30% of the mean, so that ten (n=10) runs will be simulated for each of the possible 33 (b=33 out of: 11 differing amounts of people x 3 differing variances) combinations of variables. The corresponding hypothesis states that the duration decreases with each additional employee. Experts forecast that the influence of the number of employees will far exceed the boundary-defined duration variable. Therefore, it was the total duration, forecasted through the simulation model, which was to be analyzed.

Simulation Result

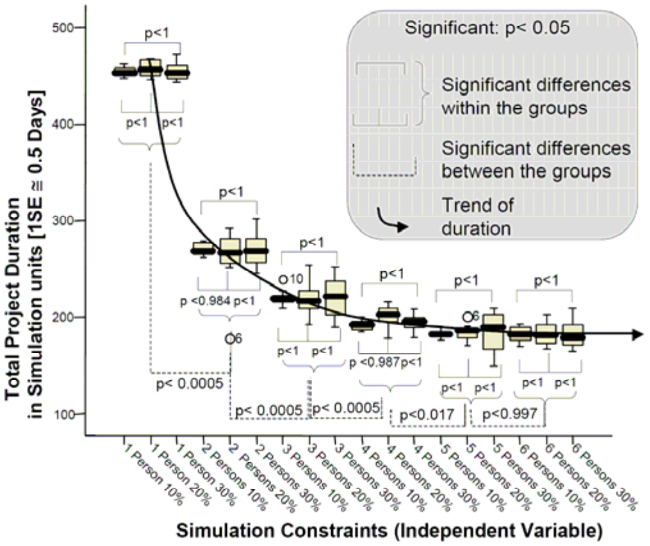

Figure 5: Dependencies between the total Project Duration and the number of employees and the variance of the expected value of activity duration time

The results (see Figure 5) were first examined on the basis of significant differences in duration. Through a one-way analysis of variance (ANOVA, $\alpha = 0.05$) it is shown that there is no significant difference within the groups that have the same number of employees. This confirms the hypothesis that with any of the possible deviations from the expected value of duration time (between 10% and 30%) that are regarded in the simulation, no significant change in total duration time takes place. This is supported independently of the predicted duration and describes a balancing effect on the variance of a large number of activities (a=79). Experience shows, however, that projects usually do encounter delays, which is why the variance in the re-design of the simulation should be replaced by a right-skewed β-distribution.

The simulation further shows that the duration can be reduced by approximately 60% through employment of more than five persons. After employment of more than six persons though, no significant reduction in duration can be measured. This is due to the project structure's task network in which no more than five tasks can be carried out at the same time, thereby also not being able to be processed by more employees. These circumstances change when more persons can be employed simultaneously for the processing of specific activities. Task sharing within a task is promoted through this, and the resulting implications were examined in further studies. Subsequent reasons for an unwanted short duration through a high number of employed organizational units lie in synchronous communications. These occur in specific intervals, lying between the tasks, and thereby occupy the required persons of the participating organizational units. In doing so, the employees are picked from the task network and "scheduled" for the discussion through the simulation. These employees can process no other tasks during this time. These communication relationships are a particular feature of development processes so that the high significance assigned to them through the simulation corresponds to actual conditions.

Examination of Dependency between Number of Work Tools and Total Duration

According to results of the first examination, the parameter "number of persons" was set to the optimal number of six employees (see Figure 6).

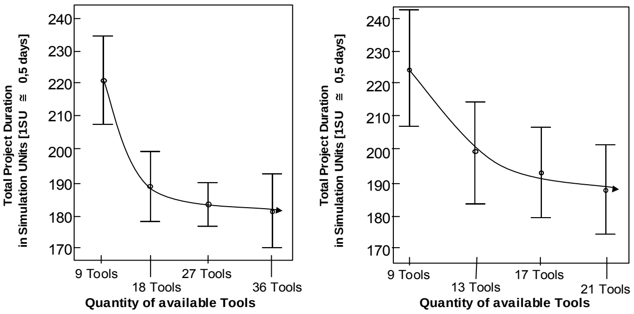

Figure 6: Connections between the simulated duration and the quantity of tools

Due to the non-significant differences concerning the distribution of variance of the expected project duration (see Figure 5) it was set to 30%. Ten simulation runs were conducted for each of the set parameter combinations. In the variation of work tools, however, their total quantity does not play a crucial role; instead, the number of very specific work tools, depending on the structure of the project, does.

Thus, the minimum requirements of the selected example process (in this case, Polyamide 6) are met for processing of various tasks for which the process' nine different work tools are needed, and for which each work tool must be available at least once.

Moreover, several work tools are needed only once or only in a work area with sequentially run tasks; additional work tools of the same type then no longer have a positive influence on the duration of the project.

To substantiate this fact, two different procedures took place. In first runs the quantity of all nine work tools was increased; test runs with nine, 18, 27 and 36 work tools were accomplished. Next, the same was done for the quantity of four selected work tools whose increase in number could also have an influence on the duration of the example process due to its structure (runs with nine, 13, 17 and 21 work tools).

Simulation Results

The results of both of these approaches are displayed in Figure 5. The hypothesis that the simulation time is not based solely on the number of work tools, rather on their properly combined quantity, can clearly be seen in the diagram. The results of the test runs in which all tools were duplicated without any preconceived expectations are displayed on the left side and the other ones on the right.

In the second runs only four of the nine work tools were added in each case since the remaining five work tools would only be needed once in the entire project, or in sequentially occurring tasks of an area.

The naive duplication of the 18 work tools produces the same results as a quantity of 13 work tools of which only the most necessary ones were duplicated. The same can be said for the work tool quantities of 27 and 17, as well as 36 and 21.

When the process of the respective test runs is taken into consideration, it can be noted that after a quantity of 17 work tools, or as the case may be, 27, no further significant improvement in simulation time can be achieved. A slight regressive tendency can be seen when there is an additional increase in quantity. This can be explained through the structure of the project in which apparently no more than three identical work tools are needed simultaneously.

FUTURE RESEARCH

The presented approach to the research project will be further developed in the future in close collaboration with enterprises in the chemical engineering industry. In addition, attributes and correlations that were not contained in the theoretically created example process, and to which, along with iterations and probability rich decisions, the formation of tool and task groups with similar job specifications belong, are added. The current scattering task processing times following the normal distribution must, in support of the phenomenon that tasks tend towards longer processing times, be changed through a right-skewed beta distribution. This and several other parameters are determined and quantified via ergonomic methods. Furthermore, the correlations of individual factors are empirically calculated through the modeling of several example processes.

The planned sensitivity analysis serves the validation of the simulation results and is to make possible a transfer of the realizations to planned work processes.

The long term goal is a round planning support through project combinations capable of simulation in order to increase the validity and the time and resource planning. Thus, improved risk management in daily project planning is also allowed for.

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