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A DESIGN PROCESS MODELING APPROACH INCORPORATING NONLINEAR ELEMENTS

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ABSTRACT

This paper extends the literature of engineering design process modeling. We focus on the modeling of design iterations using a task-based description of a development project. We present a method to compute process performance and to relate this outcome to critical activities within the process.

Design tasks are modeled as discrete-event activities with design information flowing between them. With every design task, we associate process characteristics such as the completion time and cost per time unit for the task. These characteristics can change with the advance of the design process. The method is especially suited for comparison of different design processes on the basis of overall process costs and lead time.

In order to illustrate the method a simple design process was modeled as an example. Based on this model the process lead time distribution and the process costs were simulated.

1 INTRODUCTION

The costs of a product development project are roughly proportional to the number of people involved and the duration of the project (Ulrich and Eppinger, 1995). For today's manufacturing firms a well managed product development process is therefore an important factor to stay competitive. Process modeling can be one course of action to discover key activities that influence process lead time and process costs.

In order to be able to compare different design processes, it is important to estimate their expected lead times. It is also helpful to understand why the lead time varies. Sensitivity studies can be a complement to design process modeling in order to gain further insight into the iteration process. Key activities which strongly influence lead time and process costs can be identified through sensitivity analysis.

When engineering costs are also incorporated in the model, the costs of the development process can be calculated. This makes the method well suited for comparison of different processes. The fastest process is not necessarily the cheapest one. For example, a process which involves several parallel activities may be more expensive than one where the work is done sequentially.

2 DESIGN PROCESS MODELING

Iteration is fundamental to the design process, as is stated by prior work in this area (Eppinger et al., 1994, Eppinger et al., 1997, Smith and Eppinger, 1997a, Smith and Eppinger, 1997b, Steward, 1981). An increased understanding of design iteration will enlarge our understanding of the design process. Iterations result from a coupled design task structure, one in which the (coupled) tasks require information from each other (Eppinger et al., 1994).

Generally there are two different ways to execute coupled design tasks: sequential iteration or parallel iteration. Prior models (Eppinger et al., 1997 and Smith and Eppinger, 1997b) describe methods to depict sequential iterations where coupled tasks are performed in sequence and rework is considered by a probabilistic chance of feedback to earlier tasks. Both the task time and the rework probability are constant with time. A parallel iteration model is presented by Smith and Eppinger (1997a), where the iterations are carried out in parallel and the amount of rework decreases in a linear manner. Adler et al.

(1995) model a scenario with concurrent projects and resource constraints. Engineering resources are modeled as workstations and projects as jobs. A job in their model is either receiving service from a workstation or queuing. Iterations in their modeling approach are purely sequential with fixed characteristics.

Related work has also been done by Austin et al. (1995), where the construction design process is modeled as a discrete event system. Bell et al. (1992) modeled a product development process using the dynamic systems metaphor. The design process is modeled as purely sequential or parallel. They focus on computational design, considering process lead time, costs, and design quality expressed in terms of objective functions. In parallel-task scenarios, iteration is required to resolve conflicting goals. Christian and Seering (1995) model design process dynamics based on a detailed representation of activities taking place among several designers in a team. This approach allows both sequential and parallel iterations as well as overlapping.

The approach presented in this paper follows most closely from Eppinger et al. (1997a). We combine both sequential and parallel execution of design tasks in a more general process model. This is possible due to the way that process lead times are computed. Some nonlinear properties can be modeled, i.e. the task time and the probability of rework can vary with the number of iterations completed. The introduction of a cost factor adds another novel dimension to the process model.

3 MODELING APPROACH

Design process modeling, as implemented here, is based on the observation that a design process is comprised of a number of smaller design activities. The process can be modeled by tracking design information that is exchanged between different design tasks. Work is executed as information flows to the design tasks. In such models both parallel and sequential flows can often be observed.

3.1 MODEL ELEMENTS

The model elements include two types: design tasks and design reviews. We connect these by the design information/work flows.

Design Tasks- With every design task, we associate characteristics of execution time and task cost per time unit, as described in figure 1.

To create a flexible and accurate model, we allow the task characteristics to vary with the number of iterations done. Consider for example a design process with a large amount of CAD modeling. In the first design iteration the CAD models have to be created, but in the second iteration they need only to be modified, which is less time intensive. This would correspond to a step reduction in task time as shown in figure 1. A task in which the execution time decreases with every design iteration can be modeled as a "learning-by-doing" task with an associated learning curve function.

Since the analysis method is based on a nonlinear approach, even an arbitrary functional or random relationship between an individual task duration and the number of design iterations is conceivable. However, the simplest case is also possible— a constant task time.

Design Reviews- The design review model element (shown in figure 2) depicts the probability of proceeding forward to the next design task, otherwise the process flows back to an earlier task. The design review is evaluated with the help of a random function. The characteristics of the design review can also be a function of the number of iterations. Again, the relationship between number of iterations and design review probability can be a step in probability, a "learning-by-doing" function, or simply constant.

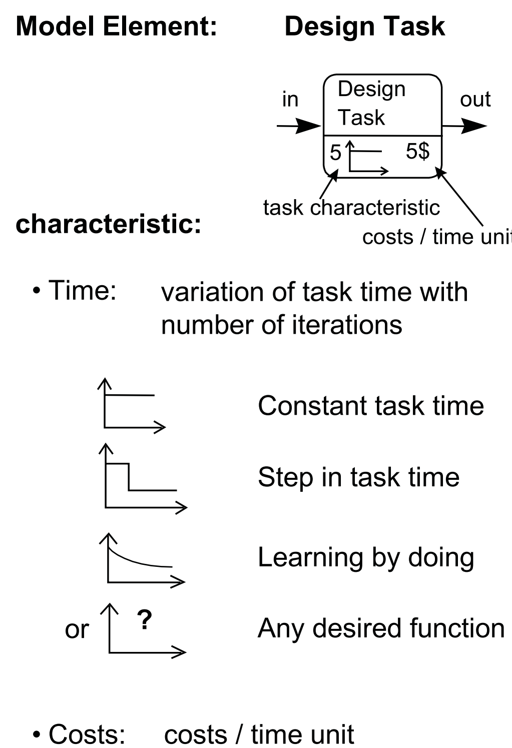

Figure 1: Characteristics of the model element ***design task.***

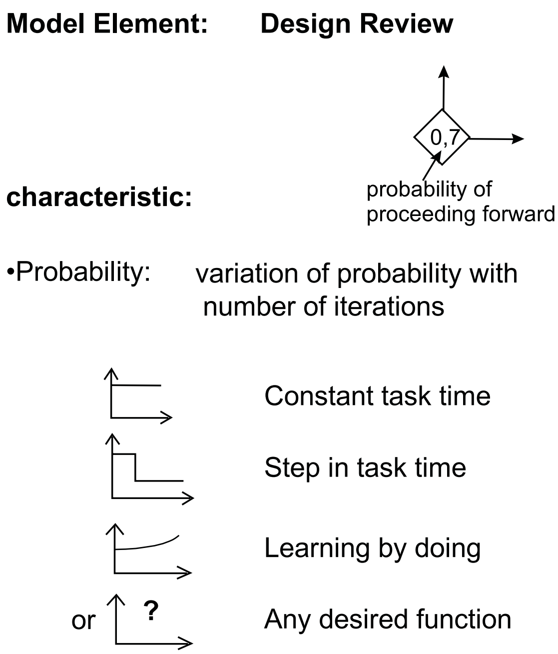

Figure 2: Characteristics of the model element ***design review.***

3.2 COMPUTATION OF LEAD TIME AND PROCESS COSTS

The nonlinear, probabilistic design process model is analyzed using one of two numerical methods: modified Monte-Carlo simulation or depth-first search, depending upon the functional form of the model elements.

In the modified Monte-Carlo method, the input signal to the first model element is an impulse. As the impulse passes through the model network, the appropriate task execution times and costs are accumulated. Each time the impulse passes a design review, a probabilistic choice is made to determine the direction to proceed. The likelihood of the path is calculated by multiplying the probabilities at each design review passed by the impulse. When the final task is reached, the path is stored together with its lead time, cost, and probability, unless this specific path has already been found earlier. By calculating the exact probability of each path found, we do not rely on a large number of simulation runs to determine the likelihood of the paths found. Different paths through the process model can result in different probabilities with the same lead time. In this case the path probabilities are added up to one single probability for that specific lead time. The probabilities of all paths found are then summed up to an accumulated probability which is used as a measure to stop simulation when close to 100% is reached (say 99%). Since the number of paths is infinite it is impossible to find them all. The paths that have not been found have a very low probability of occurring.

In order to speed up the simulation, one could introduce an additional probability in the design review elements. This can be used to steer the impulse propagating through the model in a more efficient manner. This figure can be changed as a function of the accumulated probability, so that with increasing probability the impulse discovers the less likely paths. However, for the calculation of process probability the original (model) probability value is used. After a few simulations the most common paths are found. With this method, the likelihood of finding the paths with low probabilities is increasing with the number of simulations done and the time to reach a certain accuracy decreases significantly.

In the depth-first search method, the network is fully explored by enumerating (almost) all possible paths. The analysis begins by tracing the impulse through the process, accumulating time, cost, and probability, until a design review is reached. One path is chosen at this point, but the alternate path is noted (on a stack) for future exploration. A path is followed until either the final task is reached or a very low probability is reached (say 0.1%). All paths of interest are thus identified in a rather efficient manner. Note that this depth-first method is only appropriate where the design task execution times and design review probabilities are explicit functions of the state (number of iterations and/or accumulated duration), not random functions.

The outcome of these analyses is the list of all paths found, their lead times, costs and probabilities. From these data, the expected lead time and costs can be computed. Not all possible paths in the model can be found, therefore the expected lead time can only be calculated approximately. The paths that not have been found are likely to have low probability values and long lead times, which leads to a slight underestimation of the expected lead time.

The complete lead time distribution can also be plotted, as shown in figure 4 for the example in the next section. It also shows how the lead time varies. If the accumulated probability is plotted on the same graph, as shown in figure 4, one can say what the likelihood is that the design process will be finished within a certain time. Combining this with the expected cost of each lead time, as shown in figure 4, one can understand the expected cost of the development process. The results shown are computed with the help of the modified Monte-Carlo method.

The model analysis handles design tasks executed in parallel. The beginning of a parallel activity flow is called a fork and the finish is a joint. These paths are depicted as arrows in the information flow model diagram. When the impulse passes a fork it splits up into as many impulses as there are arrows. The impulses propagate through the model until a joint is reached. At the joint, the incoming impulses of each parallel path are delayed until all impulses have arrived, and one is passed through. After the joint, only one impulse is used for evaluation.

3.3 SENSITIVITY ANALYSIS

A sensitivity analysis of the design process provides insight as to how each task and design review influences overall lead time and cost, allowing us to focus improvement efforts accordingly. The expected value and distribution of lead time and cost are dependent on the task characteristics and the probabilities in the design reviews. The sensitivity of the expected value of the lead time or cost can be calculated as the relative change in expected value due to a small change in a parameter, e.g. a task characteristic or a design review probability. If for instance L represents the lead time and k a parameter of interest, the sensitivity of L to changes in k is given by:

$$S_k^L = \frac{\Delta E[L]/E[L]}{\Delta k/k}$$, according to Eppinger et al (1997)

4 TEST CASE

Here an industrial development process is taken as a test case to illustrate the modeling approach and the analysis methods. The input data to this basic model are obtained by interviewing the engineers involved.

The development process studied is that of hydraulic pump design at a manufacturer of heavy mobile equipment. The model is depicted in figure 3 below.

Inputs to the process are constraints such as the fluid to be used, working conditions, rotational speed, pressure and so forth. In the concept design and preliminary design tasks, parameters such as pump type, the material to use, lubrication issues, bearings, and physical layout are established. Both of these tasks have constant lead time and are relatively inexpensive. The probability of rework is low (30% to start) and decreasing with the number of iterations executed.

The next phase is where the detailed design takes place. The product design task is not very time consuming because most parameters are already set. Product testing includes prototyping and is the most expensive task due to the large amount of hardware and engineering time involved. Because of the uncertainties in the analysis methods used in detailed design the likelihood of having to repeat the product design and testing phase is high.

In parallel with product design and testing, the manufacturing process design is performed. When doing these tasks in parallel the lead time is only dependent upon the most time consuming path (product design and testing). On the other hand, both paths contribute to the total process cost. The process continues with the manufacturing analysis and eventually a final design review before completion.

4.1 RESULT

The lead time distribution of the development process is shown in figure 4, together with the cumulative probability and the expected value of lead time. With the help of such a graph it is possible to get a sense of the performance variation within a development process.

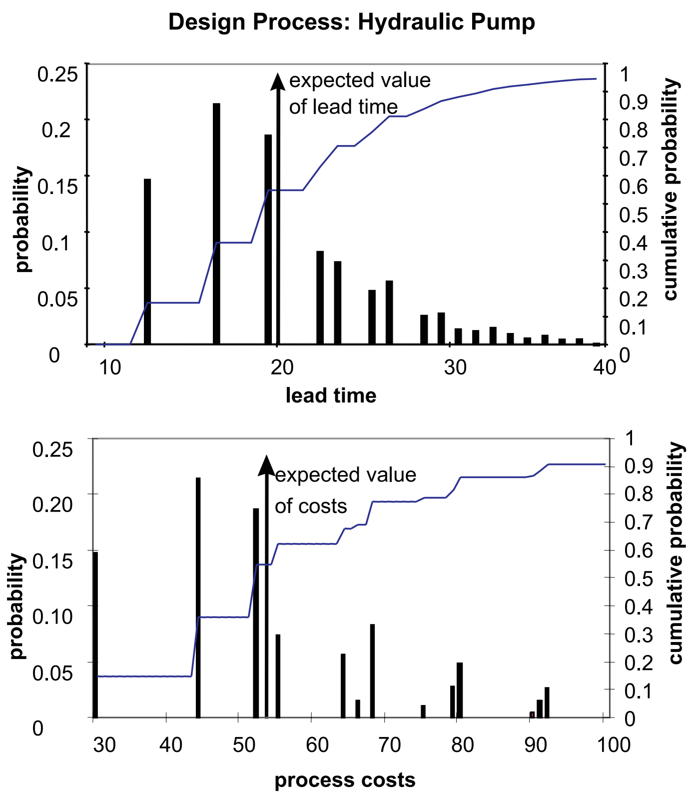

Figure 4: Lead time and cost distribution of the pump development process.

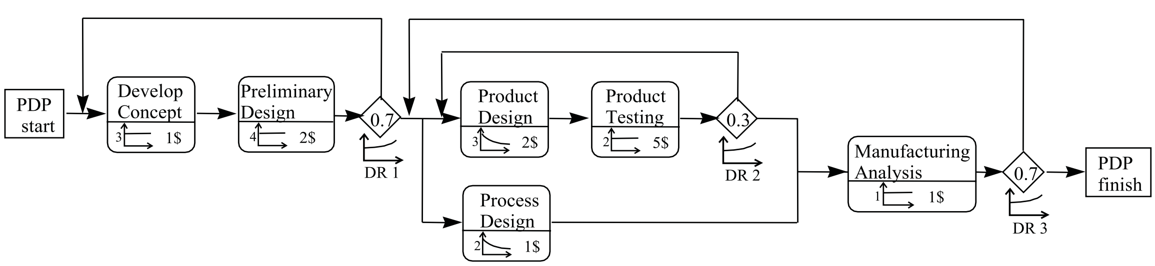

Figure 3: Hydraulic pump development process

The graph shows the lead times of all paths shorter than 40 time units. The shortest lead time possible is 13 time units and the expected value of lead time is 20.4 time units. The likelihood of finishing within a certain lead time can also be read from this graph, e.g. the likelihood of completing the development process within 25 time units is approximately 70%. This measure helps to understand the variation of the process lead time and the schedule risk of the development process.

The associated cost distribution and the expected cost of the development process are graphed in figure 4. The cost and the lead time distribution are similar, because the cost is implemented as proportional to the task lead time. When analyzing just one development process this might be superfluous, but when more development processes are compared it adds a useful dimension to the comparison.

The results of a sensitivity analysis explain the relative importance of the parameter values in the model. The sensitivity of overall lead time and cost are calculated for changes in task lead time and design review probabilities, as shown in figures 5 and 6.

Design Task	Develop Concept	Prelim. Design	Product Design
Lead Time	0.20	0.24	0.33
Cost	0.08	0.18	0.25

Figure 5a: Lead time and cost sensitivity due to changes in task lead time

Design Task	Product Testing	Process Design	Manuf. Analysis
Lead Time	0.25	0	0.05
Cost	0.48	0.04	0.02

Figure 5b: Lead time and cost sensitivity due to changes in task lead time.

Design Review	DR1	DR2	DR3
Lead Time	-0.35	-0.15	-0.25
Cost	-0.22	-0.24	-0.38

Figure 6: Lead time and cost sensitivity due to changes in design review probability.

The sensitivity analysis confirms a general insight that tasks performed frequently are more sensitive to changes in task parameters. The positive sensitivity values indicate to what extent lead times and costs increase for positive variations of the task times. The negative sensitivity values identify that increasing forward probabilities in the design reviews shorten the process lead time and cost.

The highest cost sensitivity value is the sensitivity to the lead time of product testing, which is the most expensive task. The highest time sensitivity value is <u>not</u> for the longest-duration task. The highest time sensitivity instead is to changes in the duration of product design which is embedded within the most frequently performed iteration loop. Another insight is that the process design task has no influence on overall lead time because it is carried out in parallel with product design and testing which together have a longer lead time, but process design still affects the total cost.

The sensitivity analysis on design reviews shows that changes in the success rate of the first design review (labeled DR1) has the strongest impact on lead time. This is because an iteration in the DR1 loop takes longest time. The rate of the third design review (DR3) has the greatest impact on the process cost, because one iteration of this loop is more expensive than a repetition through the other loops in the model.

5 DISCUSSION

In this section, we discuss the assumptions and limitations of the modeling approach and the insights that can be gained by using this method to model design processes.

5.1 ASSUMPTIONS AND LIMITATIONS

The modeling approach is based on the assumption that the work flow of a design process can be described by a probabilistic rule governing the likelihood that tasks have to be executed or repeated during the design process. We assume that there are no time delays due to lack of information. (Such delays can be included in the task lead time.)

The model presented here does not take any queuing effects into account. As observed by others (Adler et al., 1995 and Eppinger et al., 1997), queuing effects can be significant. In some cases, the delays due to queuing can be longer then the actual task lead time. This is likely to happen when engineers are involved in several parallel development projects or many process steps. An approach to handle the effects of queuing using the Monte-Carlo analysis method is to model several development processes performed simultaneously. Queuing can then be taken into consideration by tracking tasks that share resources and assuring that when one task is executed the others have to queue up. The queue may then be treated using a first-in-first-out rule or any other job prioritization rule.

Computation of the expected value and the variation is done numerically, and thereby always with a certain amount of uncertainty. Using the modified Monte-Carlo method, by calculating the accumulated probability we keep track of the uncertainty.

5.2 INSIGHTS GAINED BY PROCESS MODELING

This modeling approach provides engineering teams insight into their development processes through computation of lead time probability distributions and cost variations and by sensitivity analyses. It is a powerful aid to compare and evaluate different development processes. Some of the insights and positive effects are suggested below:

- *Understanding of the process*: Studying the lead time probability distribution and the sensitivity analysis yields a deep understanding of the process. The tasks which have the greatest influence on lead time and costs can be identified and thereby focused upon when improving the process. The sensitivity analysis also identifies which design reviews launch iterations with the largest impact.

- *Evaluation of risk:* The variation of the lead time and the cost helps in estimating the budget and schedule risk of the project.

- *Comparing alternative design processes:* Our approach makes it possible to compare different design processes in terms of lead time and development cost distributions. For example, performing more tasks in parallel may reduce lead time but may raise development costs.

6 CONCLUSION

The modeling approach presented here provides a powerful and flexible method for modeling and analysis of development processes. The modeling method is nonlinear and incorporates dynamic changes of design conditions in a straightforward manner without expanding the model. Both sequential and parallel work flow can be modeled in a natural way. By incorporating both process lead time and cost, this method is well suited for comparison of different development processes. The model provides information of the expected value and the probability distribution of lead time and costs. By conducting sensitivity analyses on the lead time and cost due to changes in model parameters, a deeper insight into the iterative development process is gained.

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