A Propose Method of MODELING move toward Incorporate NONLINEAR Fundamentals

Dr.SK.Poddar[1],K.Siddesha[2]

Professor in Mechanical Engineering (UOA), MNNIT, Allahabad[1], dr.skpoddar56@gmail.com
Research Scholar in Mechanical Engineering,University of Allahabad[2], m_siddesh@yahoo.com

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. 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 costscan be identified through sensitivity analysis.When engineering costs are also incorporated in the model,the costs of the development process can be calculated. Thismakes the method well suited for comparison of differentprocesses. The fastest process is not necessarily the cheapestone. For example, a process which involves several parallelactivities may be more expensive than one where the work isdone sequentially.

2 DESIGN PROCESS MODELING

Iteration is fundamental to the design process, as is statedby prior work in this area. An increased understanding of design iteration will enlarge our understanding of the design process.Iterations result from a coupled design task structure, one inwhich the (coupled) tasks require information from each other.Generally there are two different ways to execute coupleddesign tasks: sequential iteration or parallel iteration. Priormodels (Eppinger et al., 1997 and Smith and Eppinger, 1997b)describe methods to depict sequential iterations where coupledtasks are performed in sequence and rework is considered by aprobabilistic chance of feedback to earlier tasks. Both thetask 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 anddesign reviews.We connecttheseby thedesigninformation/work flows.Design Tasks- With every design task, we associatecharacteristics of execution time and task cost per time unit, asdescribed in figure 1.To create a flexible and accurate model, we allow the taskcharacteristics to vary with the number of iterations done.Consider for example a design process with a large amount ofCAD modeling. In the first design iteration the CAD modelshave to be created, but in the second iteration they need only tobe modified, which is less time intensive. This wouldcorrespond to a step reduction in task time as shown in figure 1.A task in which the execution time decreases with every designiteration can be modeled as a "learning-by-doing" task with anassociated learning curve function.Since the analysis method is based on a nonlinearapproach, even an arbitrary functional or random relationshipbetween an individual task duration and the number of designiterations is conceivable. However, the simplest case is alsopossible— a constant task time.Design Reviews- The design review model element(shown in figure 2) depicts the probability of proceedingforward to the next design task, otherwise the process flowsback to an earlier task. The design review is evaluated with thehelp of a random function. The characteristics of the designreview can also be a function of the number of iterations. Again,the relationship between number of iterations and design reviewprobability can be a step in probability, a "learning-by-doing"function, or simply constant.

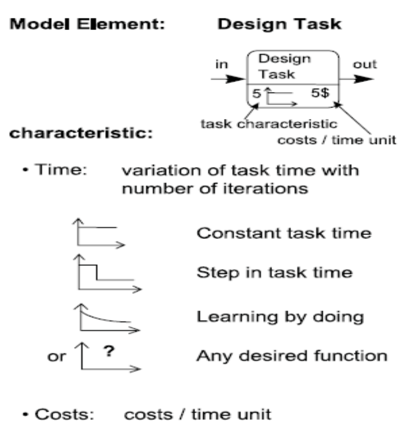

Figure 1: Characteristics of the model element ***design task.***

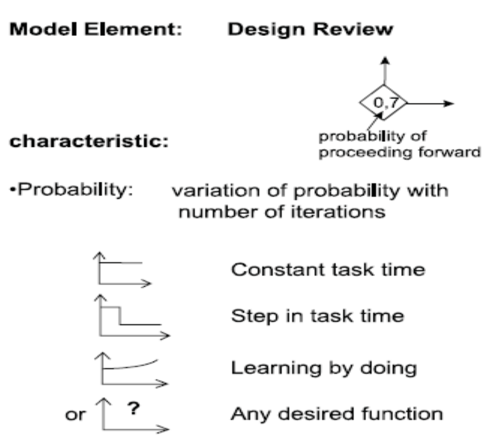

Figure 2: Characteristics of the model element ***design review.***

3.2 COMPUTATION OF LEAD TIME AND PROCESSCOSTS

The nonlinear, probabilistic design process model isanalyzed using one of two numerical methods: modified Monte-Carlo simulation or depth-first search, depending upon thefunctional form of the model elements.In the modified Monte-Carlo method, the input signal tothe first model element is an impulse. As the impulse passesthrough the model network, the appropriate task executiontimes and costs are accumulated. Each time the impulse passes adesign review, a probabilistic choice is made to determine thedirection to proceed. The likelihood of the path is calculated bymultiplying the probabilities at each design review passed bythe impulse. When the final task is reached, the path is storedtogether with its lead time, cost, and probability, unless thisspecific path has already been found earlier. By calculating theexact probability of each path found, we do not rely on a largenumber of simulation runs to determine the likelihood of thepaths found. Different paths through the process model canresult in different probabilities with the same lead time. In thiscase the path probabilities are added up to one singleprobability for that specific lead time. The probabilities of allpaths found are then summed up to an accumulated probabilitywhich is used as a measure to stop simulation when close to100% is reached (say 99%). Since the number of paths isinfinite it is impossible to find them all. The paths that have notbeen found have a very low probability of occurring.In order to speed up the simulation, one could introducean additional probability in the design review elements. Thiscan be used to steer the impulse propagating through the modelin a more efficient manner. This figure can be changed as a function of the accumulated probability, so that with increasingprobability 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 mostcommon paths are found. With this method, the likelihood offinding the paths with low probabilities is increasing with thenumber of simulations done and the time to reach a certainaccuracy decreases significantly.In the depth-first search method, the network is fullyexplored by enumerating (almost) all possible paths. Theanalysis begins by tracing the impulse through the process,accumulating time, cost, and probability, until a design reviewis reached. One path is chosen at this point, but the alternatepath is noted (on a stack) for future exploration. A path isfollowed until either the final task is reached or a very lowprobability is reached (say 0.1%). All paths of interest are thusidentified in a rather efficient manner. Note that this depth-firstmethod is only appropriate where the design task executiontimes and design review probabilities are explicit functions ofthe state (number of iterations and/or accumulated duration),not random functions.The outcome of these analyses is the list of all pathsfound, their lead times, costs and probabilities. From thesedata,the expected lead time and costs can becomputed. Not allpossible paths in the model can be found, therefore the expectedlead time can only be calculated approximately. The paths thatnot have been found are likely to have low probability valuesand long lead times, which leads to a slightunderestimation ofthe expected lead time.

The complete lead time distribution can also be plotted, asshown in figure 4 for the example in the next section. It alsoshows how the lead time varies. If the accumulated probabilityis plotted on the same graph, as shown in figure 4, one can saywhat the likelihood is that the design process will be finishedwithin a certain time. Combining this with the expected cost ofeach lead time, as shown in figure 4, one can understand theexpected cost of the development process.

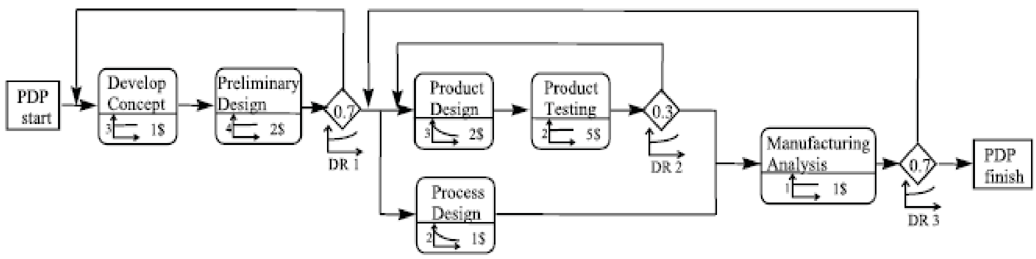

Figure 3: Hydraulic pump development process

The results shownare computed with the help of the modified Monte-Carlomethod.

The model analysis handles design tasks executed inparallel. The beginning of a parallel activity flow is called afork and the finish is a joint. These paths are depicted as arrowsin the information flow model diagram. When the impulsepasses a fork it splits up into as many impulses as there arearrows. The impulses propagate through the model until a jointis reached. At the joint, the incoming impulses of each parallelpath are delayed until all impulses have arrived, and one ispassed through. After the joint, only one impulse is used forevaluation.

3.3 SENSITIVITY ANALYSIS

A sensitivity analysis of the design process providesinsight as to how each task and design review influencesoveralllead time and cost, allowing us to focus improvement effortsaccordingly. The expected value and distribution of lead timeand cost are dependent on the task characteristics and theprobabilities in the design reviews. The sensitivity of theexpected value of the lead time or cost can be calculated as therelative change in expected value due to a small change in aparameter, e.g. a task characteristic or a design reviewprobability. If for instance L represents the lead time and k aparameter of interest, the sensitivity of L to changes in$k$ isgiven 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 testcase to illustrate the modeling approach and the analysismethods. The input data to this basic model are obtained byinterviewing the engineers involved.The development process studied is that of hydraulicpump design at a manufacturer of heavy mobile equipment. Themodel is depicted in figure 3 below.Inputs to the process are constraints such as the fluid to beused, working conditions, rotational speed, pressure and soforth. In the concept design and preliminary design tasks,parameters such as pump type, the material to use, lubricationissues, bearings, and physical layout are established. Both ofthese tasks have constant lead time and are relativelyinexpensive. 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 becausemost parameters are already set. Product testing includesprototyping and is the most expensive task due to the largeamount of hardware and engineering time involved. Because ofthe uncertainties in the analysis methods used in detailed designthe likelihood of having to repeat the product design and testingphase is high.Inparallelwithproductdesignand testing,themanufacturing process design is performed. When doing thesetasks in parallel the lead time is only dependent upon the mosttime consuming path (product design and testing). On the otherhand, both paths contribute to the total process cost. Theprocesscontinueswith themanufacturinganalysisandeventually a final design review before completion.

4.1 RESULT

The lead time distribution of the development process isshown in figure 4, together with the cumulative probabilityandthe expected value of lead time. With the help of such a graph itis possible to get a sense of the performance variation within adevelopment 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.

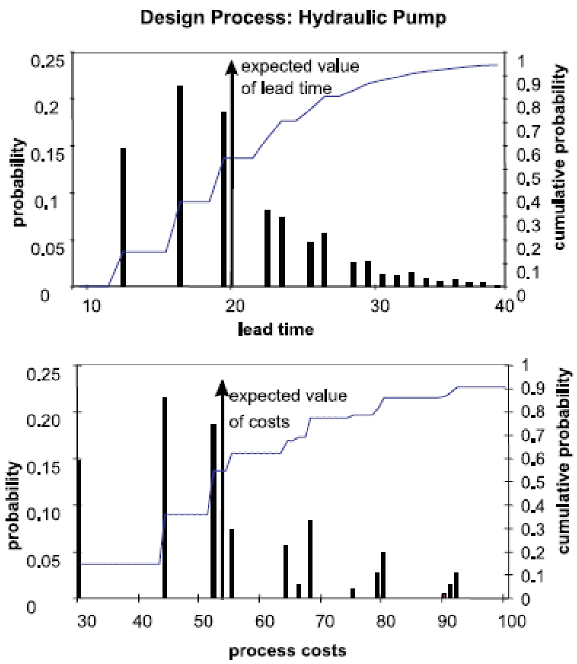

Figure 4: Lead time and cost distribution of the pump development process.

The results of a sensitivity analysis explain the relativeimportance of the parameter values in the model. The sensitivityof overall lead time and cost are calculated for changes in tasklead time and design review probabilities, as shown in figures 5and 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 thattasks performed frequently are more sensitive to changes in taskparameters. The positive sensitivity values indicate to whatextent lead times and costs increase for positive variations ofthe task times. The negative sensitivity values identify thatincreasing forward probabilities in the design reviews.Shortenthe process lead time and cost.The highest cost sensitivity value is the sensitivity to thelead time of product testing, which is the most expensive task.The highest time sensitivity value is not for the longest-durationtask. The highest time sensitivity instead is to changes in theduration of product design which is embedded within the mostfrequently performed iteration loop. Another insight is that theprocess design task has no influence on overall lead time
because it is carried out in parallel with product design andtesting which together have a longer lead time, but processdesign still affects the total cost.The sensitivity analysis on design reviews shows thatchanges in the success rate of the first design review (labeledDR1) has the strongest impact on lead time. This is because aniteration in the DR1 loop takes longest time. The rate of thethird design review (DR3) has the greatest impact on theprocess cost, because one iteration of this loop is moreexpensive than a repetition through the other loops in themodel.

5 DISCUSSION

In this section, we discuss the assumptions and limitationsof the modeling approach and the insights that can be gained byusing this method to model design processes.

5.1 ASSUMPTIONS AND LIMITATIONS

The modeling approach is based on the assumption thatthe work flow of a design process can be described by aprobabilistic rule governing the likelihood that tasks have to beexecuted or repeated during the design process. We assume that there are no time delays due to lack of information. (Suchdelays 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., 1995and Eppinger et al., 1997), queuing effects can be significant. Insome cases, the delays due to queuing can be longer then theactual task lead time. This is likely to happen when engineers are involved in several parallel development projects or manyprocess steps. An approach to handle the effects of queuingusing the Monte-Carlo analysis method is to model severaldevelopment processes performed simultaneously. Queuing canthen be taken into consideration by tracking tasks that shareresources and assuring that when one task is executed the othershave 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 isdone numerically, and thereby always with a certain amount ofuncertainty. Using the modified Monte-Carlo method, bycalculating the accumulated probability we keep track of the
uncertainty.

5.2 INSIGHTS GAINED BY PROCESS MODELING

This modeling approach provides engineering teamsinsight into their development processes through computationof lead time probability distributions and cost variations and bysensitivity analyses. It is a powerful aid to compare and evaluatedifferent development processes. Some of the insights andpositive effects are suggested below:

- *Understanding of the process*: Studying the lead timeprobability distribution and the sensitivity analysis yields adeep understanding of the process. The tasks which havethe greatest influence on lead time and costs can beidentified and thereby focused upon when improving theprocess. The sensitivity analysis also identifies whichdesign reviews launch iterations with the largest impact.

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

- *Comparing alternative design processes:* Our approachmakes it possible to compare different design processes interms of lead time and development cost distributions. Forexample, performing more tasks in parallel may reduce leadtime but may raise development costs.

6 CONCLUSION

The modeling approach presented here provides apowerful and flexible method for modeling and analysis ofdevelopment processes. The modeling method is nonlinear andincorporates dynamic changes of design conditions in astraightforward manner without expanding the model. Bothsequential and parallel work flow can be modeled in a naturalway. By incorporating process lead time and cost, thismethod is well suited for comparison of different developmentprocesses. The model provides information of the expectedvalue and the probability distribution of lead time and costs. Byconducting sensitivity analyses on the lead time and cost due tochanges in model parameters, a deeper insight into the iterativedevelopment process is gained.

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