A SIMULATION MODEL FOR MANAGING ENGINEERING CHANGES ALONG WITH NEW PRODUCT DEVELOPMENT

Weilin Li and Young B. Moon
L. C .Smith College of Engineering & Computer Science, Syraceuse University, 223 Link Hall, Syracuse, NY 13244, U.S.A.

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Abstract: This paper presents a process model for managing Engineering Changes (ECs) while other New Product Development (NPD) activities are being carried out in a company. The discrete-event simulation model incorporates Engineering Change Management (ECM) into an NPD environment by allowing ECs to share resources with regular NPD activities. Six model variables - (i) overlapping, (ii) NPD departmental interaction, (iii) ECM effort, (iv) resource constraints, (v) arrival rate, and (vi) resource using priority - are explored to identify how they affect lead time and productivity of both NPD and ECM. Decision-making suggestions for minimum EC impact are then drawn from an overall enterprise system level perspective based on the simulation results.

1 INTRODUCTION

Today's increasingly competitive market forces any corporations who develop new products to look into all the possible areas of improvement in their entire product lifecycle management process. One of the areas that have been overlooked in the past is the Engineering Change Management. Engineering Change Management (ECM) refers to a collection of procedures, tools, and guidelines for handling modifications and changes to a product after the product has been released to the market. (Terwiesch and Loch, 1999; Bhuiyan, 2006) In reality, an ECM is a norm rather than an exception in any typical product development firm. Consequently, ECM plays a critical role in finally realizing actual profits from new product development efforts.

While the demand for more effective ECM has increased, managing EC also became more efficient than ever due to various advancements in tools and technologies. The digitalized virtual design and prototyping tools provide greatly increased efficiency but with shorter cycle time and less cost. The integrated Enterprise Resource Planning system (Moon, 2007) assists ECM by eliminating redundant documentation, assuring data consistency, and maximizing data sharing among affected parties. The main question is how to bring these new available aids to enhance the ultimate new product development process. Particularly, we are interested in investigating how ECM affects general New Product Development (NPD) activities and vice versa.

Most of previous researches studying the ECM processes focused on general administrative rules for an organization to follow to reduce long lead-time of ECMs, regardless of the types of firms and products or other diverse operational conditions. (Wright, 1997) However, the following several important issues impact both NPD and ECM significantly:

First, product development firms of different sizes design and manufacture products differently with varying degrees of complexity. In other words, the frequency of developing new products and that of handling engineering changes can be quite different from one company to another. Also in general, engineering change requests (ECRs) occur in far more random patterns. Second, ECRs that require modification or rework in different NPD stages need different amount of time and effort. Third, firms may choose to employ different structure for its NPD process depending on how they handle coupled product development activities and cross-functional interaction among departments. Fourth, NPD and ECM activities normally compete for limited resources available in a firm. Therefore,

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firms have to allocate available resources between NPD and ECM to maximze their ultimate profits.

Weighing the above four major factors, companies may adopt different NPD and ECM strategies. The objective of this research is to provide insightful decision-making suggestions for companies regarding how engineering changes should be implemented with minimal adverse effects on normal NPD activities. We propose to model and simulate the EC implementation within a multi-project development environment to answer the following questions:

1. How important is ECM for a firm that is engaged in developing new products?
2. What are the key contributors to long lead times in NPD in relation with ECM? And vice versa.
3. What are the key contributors to low production rates in NPD in relation with ECM? And vice versa.
4. What is an optimal way of allocating limited resources between NPD and ECM?

A discrete-event simulation methodology is adpoted to model both NPD and ECM process together, primarily because of their complexity.

2 LITERATURE REVIEW

The review of papers until 1995 was done by Wright. (Wright, 1997) The author categorized the EC related papers into two main topics, computer-based “tools” for the analysis of EC problems and “methods” to reduce the impact of ECs on manufacturing and inventory control. We can find that most of the publications in that time period predominantly focused on the EC administrative guidelines and control mechanisms. An important observation by Wright is that understanding of the positive effect EC can provide for product improvement and enhanced market performance is long omitted by EC research.

Terwiesch and Loch presented a process-based view of ECM. (Terwiesch and Loch, 1999) They showed by an industrial case study that a complicated and congested administrative support process is one of the root causes of long lead time and high cost. Based on the field study, they indentified five key contributors to lengthy ECO lead time: complex ECO approval process, scarce capacity and congestions, setups and batching, snowballing changes, and organizational issues.

In another paper they wrote, an analytical framework that explains the extreme ratio between theoretical processing time and actual lead time was developed. (Loch and Terwiesch, 1999) They showed how congestion and batching influence engineering processes at a more detailed level. Based on the processing network framework, they suggested improvement strategies such as flexible work times, the grouping of several tasks, workload balancing, the pooling of resources, and the reduction of setup times.

Krishnan (Krishnan, 1997) presented a model-based framework to manage the overlapping of coupled product development activities. The author introduced two properties, upstream information and downstream iteration sensitivity, of the information exchanged between product design phases. The mathematical model and conceptual framework of the overlapped process were illustrated with industrial examples to provide managerial insights.

Bhuiyan and her co-workers built a stochastic computer model to examine how overlapping and functional interaction affect the performance measures of development time and effort under varying conditions of uncertainty. (Bhuiyan, 2004) It is the first comprehensive model using a discrete-event simulation for the entire NPD process by taking into account functional interaction at different values of overlapping under different uncertainty conditions. Development effort was also introduced, in the form of total person-days for a project, as a measure of NPD performance that was neglected by earlier researchers. A number of conclusions were drawn from the model, however, their model assumed an unlimited amount of resources, which is unrealistic in practice.

Bhuiyan’s research group has also expanded this framework to compare two methods for managing Engineering Change Requests (ECRs): immediate individual processing as issued and batch processing after accumulation. (Bhuiyan, 2006) They evaluated the effects of the methods in terms of development time and effort. The model they developed, though, has a couple of limitations: (i) the research scope only on immediate or batch processing, is too simplified compared with a large amount of ECM problems; (ii) treating all ECRs similarly is acceptable only for comparative analysis. Despite of these limitations, Bhuiyan’s model is the only study on ECM using the discrete-event simulation. Thus it inspired our model.

Browning presented a thorough literature survey on the topic of activity network-based models for NPD project management. (Browning, 2007) The paper is based upon four major categories: visualization, planning, execution and control, and project development. The author highlighted the models' main assumptions, findings, and insights. To conclude, he identified five research directions for future study: activity interactions, global process improvements, process models as an organizing structure for knowledge management, modeling in cases of uncertainty and ambiguity, and determining the optimum amount of process prescription and structure for an innovative project.

3 MODEL OF NPD AND ECM

In this section, we will introduce the framework structure, components, variables, parameter setting, and assumptions of this modeling project. Arena simulation package is used for the project.

NPD Framework

The NPD model has three *phases*, namely Concept, Design, and Production. They occur sequentially but with certain degrees of overlapping. Each phase is consisted of three sequentially numbered *activities* to represent its different stages.

Assumptions

The model assumptions are presented in the bullet form [A1], [A2], ...[An].

[A1] Each NPD project begins with an inter-arrival value of 20 days, 48 days, or 120 days depending on project size and product type. Correspondingly, the arrival rate expressed in Arena is CONST 12/yr, 5/yr, and 2/yr.

[A2] The activity duration follows a normal distribution, which represents the uncertainties in product design and development processes.

[A3] The mean value of activity duration within one phase remains the same, but increases as NPD entities proceed from Concept to Design to Production because of the increasing activity complexity since more product development tasks are involved. Detailed activity duration assignment is shown in Table 1.

[A4] When NPD arrives at a lower (or higher) rate, we assume the project to be more (or less) complicated and thus require more (or less) time to finish. The duration of an activity is set to be proportional to its arrival rate.

NPD Overlapping

In this paper we refer to *overlapping* as the partial or full parallel execution of tasks. By having this 3-phase and 3-activity framework, we are able to construct an NPD process with 0% (sequential), 33%, or 66% overlapping, while any amount between 0 and 100% can be true in real life.

Table 1: NPD Activity Duration.

NPD Arrival Rate	**NPD Activity Duration** in		
	Concept phase	Design phase	Production phase
CONST 12/yr	NORM (1.333, 0.645)	NORM (2, 0.791)	NORM (3.333, 1.021)
CONST 5/yr	NORM (3.2, 1)	NORM (4.8, 1.225)	NORM (8, 1.581)
CONST 2/yr	NORM (8, 1.581)	NORM (12, 1.936)	NORM (20, 2.5)

NPD Iteration

After each activity, there is a Decision module in which NPD entities pass through or go back by pre-assigned probability. NPD entities may go back and repeat the just-finished activity or any one of its previous activities, including activities in other phases. This rework process is called *NPD iteration*. Probability of the N-way decision by chance to go back to one certain activity for rework is also modelled.

Departmental Interaction

The concept of cross-functional integration among different functional areas during an NPD process is defined as *departmental interaction*.

One of the three departments - Marketing, Design, and Manufacturing - takes major responsibility for a phase of its own specialization, and is called *major department* during that phase. In other words, Marketing Department is the major department in Concept phase, Design Department in Design phase, and Manufacturing Department in Production phase. However, the other two departments, defined as *minor departments*, also participate in the same phase with less allocation of resources.

Two levels of departmental interaction, 60 (major dept.) - 20 (minor dept.) - 20 (minor dept.), and 40 (major dept.) - 30 (minor dept.) - 30 (minor dept.), are examined in our model. These two levels represent low and high departmental interaction with a total resource consumption of 100 number of resources.

Resource Constraints

Resources can represent staffs, computer/machine, documentation support, or any other individual server. In our model, we examined three levels resources, that is, 200, 100, or 60 numbers of resources from each department. We set the minimum number to be 60 resources per department, which is equal to the resource consumption for a major department at low level of departmental interaction, in order to ensure that the major department gets enough resource to let NPD process flow.

We assume that each resource is qualified to handle all the NPD activities in three phases.

ECM Framework

Additional assumptions for ECM model include:

[A5] One EC is confined in only one NPD activity in this model.

[A6] ECM shares the same pool of resources with that particular NPD activity by defining its queue as shared.

[A7] Concept 3, three activities in Design, and three activities in Production each have an equal chance of implementing an ECR.

[A8] Changes that are undertaken in Concept 1 and Concept 2 are not considered as ECs since within the first two NPD activities a comprehensively large number of new product ideas are gathered, discussed and modified. NPD ideas are less formally organized.

[A9] Compared with NPDs that are more likely sticking to a planned schedule, ECRs occur without expectations. So we use exponential distribution to assume ECRs' arrival.

[A10] The ECM process time is set to be proportional to its corresponding arrival rate. It also increases proportionally from phase to phase in the same fashion as NPD activity duration does. Table 2 shows the detailed process time for an ECR to be implemented within different NPD phases at three arrival rates.

ECM Effort

The amount of resources required for an EC to be processed is called *ECM effort*. Three levels of ECM effort, 2-2-2, 5-5-5 and 10-10-10, are examined in this model.

We assume that an EC consumes equal number of resources from all three departments no matter in which phase it occurs.

Table 2: ECM Process Time.

ECM Arrival Rate	**ECM Process Time** in		
	Concept phase	Design phase	Production phase
Random (EXPO) 8/mo	TRIA (0.25, 0.5, 0.75)	TRIA (0.38, 0.75, 1.12)	TRIA (0.62, 1.25, 1.88)
Random (EXPO) 4/mo	TRIA (0.5, 1, 1.5)	TRIA (0.75, 1.5, 2.25)	TRIA (1.25, 2.5, 3.75)
Random (EXPO) 2/mo	TRIA (1, 2, 3)	TRIA (1.5, 3, 4.5)	TRIA (2.5, 5, 7.5)

Resource using Priority

When there are not enough resources available for both processes, a *priority* needs to be assigned to either NPD or ECM to get resource first.

This is achieved by setting priority to seize resource in Process and Seize modules in Arena.

Running Parameters

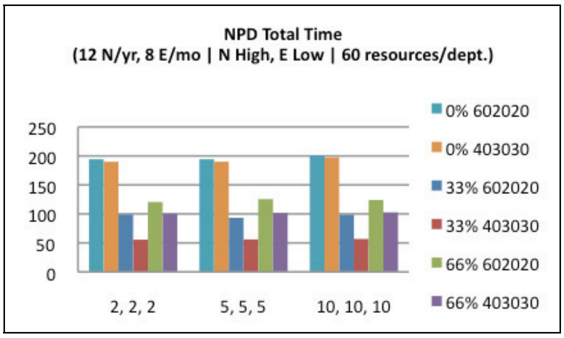
We've specified the running parameters *Hours-Per-Day* as 8 and *Work-Day-Per-Year* to be 20 days/month * 12 months/year (240 days/year). We run the model in ten replications with a replication length of 2 years.

4 RESULTS ANALYSIS

For the model described above, we analyzed the influence of resource constraint, resource using priority, overlapping, NPD departmental interaction, ECM effort, on both NPD and ECM lead time and productivity under different NPD and ECM arrival rates. Three levels of NPD and ECM arrival rates are combined in pairs according to their value. That is, high NPD arrival rate is studied with high ECM arrival rate, and low NPD arrival rate with low ECM arrival rate.

There are altogether six sets of model variables, and each of them has two or three possible values, which is summarized in Appendix B. We run the model 972 times altogether with the help of a separate application of Arena call process analyzer (PAN).

A partial results are presented in this paper due to space limitation. The following two charts show the impacts of overlapping, NPD departmental interaction, and ECM effort on NPD Total Time and Productivity under resource constraint of 60 units from each department.



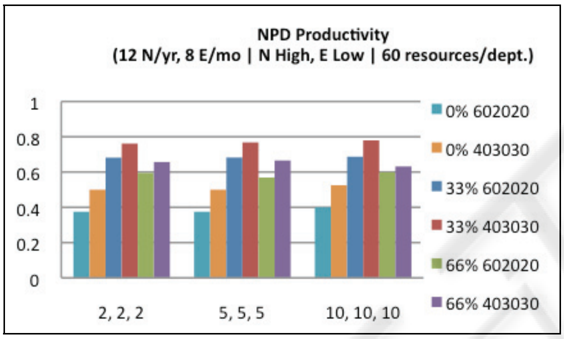


Figure 1: Simulation Results.

Based on the results we obtained, several observations are made and its possible explanations are given:

Observation	Explanation
When there are unlimited resources (200 resources/dept. in this case) for NPD and ECM activities, higher degree of overlapping results in the reduction of NPD lead time.	With more amount of overlapping, there will be more product development activities executed before the completion of the previous ones. So products are developed faster if there are enough resources available.
When there are not enough resources (60 resources/dept. in this case) for NPD and ECM activities, overlapping as much as possible is no longer recommended.	If only limited resources are given, a medium level of overlapping and high departmental interaction yields the optimal NPD lead time. Firms need to make compromise between shorter value-added time but longer wait time to grab resources under higher degree of overlapping.
As the *Number of Resources* decreases, *Productivity* of both NPD and ECM drops off, but NPD with a higher rate.	This phenomenon is pretty straightforward. When there are fewer resources available, the resource utilization raises, sometimes even exceeds 100%. Then fewer NPDs and ECMs will get adequate resources to be completed in a certain time period, runtime in this case.
As the *Number of Resources* decreases, *Lead Time* of both NPD and ECM goes up.	Even for those NPDs and ECMs that get required resources to be processed, the total time (time an entity enters the system until it exits) will be longer due to longer wait time for fewer resources that are available.
A high departmental *interaction level* results in higher productivity and shorter lead time than a low departmental interaction level, especially when resources are limited.	Because each incoming ECM may consume resources from the three departments with equal chance. With a total resource demand unchanged, if there is more departmental interaction, there will be more spare resources for the major department to execute.
The *Priority* assigned to NPD and ECM matters only when the resources are limited and the organization choose to pursue a low level of departmental interaction (60-20-20 in this paper). When high priority is assigned to NPD, productivity of NPD is about 50% higher than the situation in which high priority is given to ECM, while the productivity of ECM is just slightly lower. But at the same time, both NPD and ECM take longer to complete.	By assigning higher priority to NPD, there are more NPD entities coming out of the system without affecting ECM productivity much. However, the price to pay is the longer lead time for both NPD and ECM since there are more resource demands thus resulting in a higher overall resource utilization. Organizations face tradeoffs between productivity and lead time in this situation.
The *ECM Effort* is not the key factor of NPD/ECM Productivity. It affects NPD/ECM lead time only when the resources are limited and the organization choose to pursue a high level of departmental interaction (40-30-30 in this paper).	Recall that high level of departmental interaction means that minor departments participate more while major department allocates fewer resources in its own specialization phase. So if an ECM is complex and requires greater effort (10 resources from each department in this case), minor departments are much easier to be out of resources than low departmental interaction case.

5 CONCLUSIONS

The NPD and ECM model framework introduced above address several issues that earlier models didn't. In this model, we capture important new product design and development characteristics such as iteration and overlapping of NPD process, interaction among different functional areas, resource constraints and its using priority. We also take into account the size of NPD projects and ECRs in terms of their arrival rates and processing effort. From the simulation results, a number of conclusions can be drawn:

1) ECM is an important aspect to the success of an NPD project. On one hand, it solves safety or critical functionality problems of a product. And it reflects customer requirements or technology developments. On the other hand, it also consumes a considerable amount of product development resources which in turns affects the lead time and productivity of regular NPD activities significantly.
2) While each of the six model variables, overlapping, NPD departmental interaction, ECM effort, resource constraints, arrival rate, and resource using priority, affects the overall lead time and productivity of both NPD and ECM by some extent, the effect of resource constraints is most significant.
3) As stated in Section 4, this model addresses decision-making suggestions for firms under different organization environment and resource constraint condition. Specifically, when the resource capacity is limited, a medium level of overlapping and high departmental interaction is suggested to optimize system resource utilization.

However, there are several aspects of this model that need further investigation. First, the assumption that one EC is confined in one NPD activity is not always true. An EC that requires rework in a design activity may propagate to other activities in design or production phase. Future study should include engineering change propagation as one feature of the ECM process. Second, in the current model, we assign to an NPD entity probabilities for feedback iterations. However, when a new product project needs to go back to earlier NPD activities for a rework, subsequent activities need to be followed again no matter how many times these activities are repeated. In other words, an NPD entity has to go through again all the downstream activities after being sent back to the iteration starting point. Feed-forward flexibility and learning effects for iteration need to be considered in future work. Third, in this model, it is assumed that NPD and ECM share the same pool of resources with using priority. We could let NPD and ECM have their own dedicated resources. Or, NPD and ECM still use the same pool of resources. But ECM requests for outsourcing when resources are not available. In this case, different utility costs can be set for using resources within a department, cross departments, and for outsourcing. Fourth, besides lead time and productivity, other critical criteria such as resource utilization, total cost, and customer satisfaction, can be adopted to review and evaluate the impact of ECM throughout NPD process.

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