Proceedings of the 2011 Winter Simulation Conference
S. Jain, R.R. Creasey, J. Himmelspach, K.P. White, and M. Fu, eds.

MODELING AND MANAGING ENGINEERING CHANGES IN A COMPLEX PRODUCT DEVELOPMENT PROCESS

Weilin Li
Young B. Moon

Syracuse University
Department of Mechanical and Aerospace Engineering
263 Link Hall,
Syracuse, NY 13244, USA

ABSTRACT

Due to ever increasing competitive market place, demanding customers, and rapidly advancing technologies, corporations developing new products are forced to look into all the possible areas of improvement throughout the entire product lifecycle management process. One of the research areas that have been overlooked in the past is Engineering Change Management (ECM). This paper presents a simulation model for investigating the mutual impacts of ECM process and New Product Development (NPD) process on each other. The discrete-event simulation model incorporates ECM into an NPD environment by allowing Engineering Change (EC) activities to compete for limited resources against regular NPD activities. The goal of the research is to determine the key characteristics of ECM and NPD that affect lead time and productivity of both processes. Decisions to be made by considering EC impacts are drawn from an enterprise level systems perspective.

1 INTRODUCTION

New Product Development (NPD) refers to an entire process from idea generation, through product design and manufacturing, to bringing a new product to the market. There are general characteristics of NPD that are important to this research. First, typical companies launch their new products according to a planned schedule. NPD projects are generally well-planned in advance in terms of project specifications (including task schedule, stage gate dates, resource allocation, performance measurement, etc.), financial justification, and preliminary market and technical assessment (Brown 1995). Typically, a product development company carries out multiple NPD projects in different design and development stages at the same time. Second, though limited engineering capacity has always been a challenge to most organizations, a resource commitment to an NPD project is normally pre-determined and stable. That is, certain amounts of resources are dedicated to each NPD project as stated by the proposed resource planning. Third, despite the above-mentioned pre-determined side of NPD process, "iteration is a fundamental characteristic of complex design projects" (Cho and Eppinger 2005), which in turn causes significant departure from the initial planning, consuming more time and resources than planned, and may even lead to the failure of an NPD project. Fourth, the concept of concurrent engineering with integrated cross-functional engineering resources (Ford and Sterman 1998) has been widely embraced by both academia and industry. Following this trend, the NPD cycle is being accelerated and design errors are more likely to be discovered in early phases. On the other hand, working with preliminary information will also increase the chance of downstream iteration. Lastly, despite the fact that the NPD process is becoming more and more complex, which is attributable to the increasing volume of information involved, some general repeatable structures can be discerned since "design is something of an art but with many consistent patterns" (Browning and Ramasesh 2007).

Engineering Change Management (ECM), on the other hand, refers to a collection of procedures, tools, and guidelines for handling modifications and changes to a product item after its configuration is released (Terwiesch and Loch 1999; Huang and Mak 1999; Bhuiyan, Gregory, and Thomson 2006). Unlike the iteration within the NPD process, an engineering change can be considered as the rework during or after production. It occurs in far more random pattern compared with regular NPD projects. The amount of time and effort required for each ECM also varies from case to case. Simple changes to the manufacturing specifications of a product component may need just a few days while other changes may cause unexpected downstream change propagation and result in significant resource consumption and a long overall EC processing time. Also, ECM requires an integrated effort among project planning, engineering, manufacturing, purchasing and inventory control, sales and marketing, finance, human resources, and suppliers. Typically, there are no such cross-functional resources dedicated to resolving ECs. If there is no spare resource available when an Engineering Change Request (ECR) is made, the ECM process has to compete for the same resources that have already been assigned to regular NPD activities.

In reality, an EC is a norm rather than an exception in many product development firms. Consequently, ECM is a major competitive factor in product design and development process that should not be neglected (Eckert, Clarkson, and Zanker 2004). It plays a critical role in finalizing actual profits from new product development efforts. Companies benefit from ECM by correcting design faults, solving discovered safety or functionality issues, correcting manufacturability problems, continuously reflecting customers' requirements, responding to governmental regulations, localizing products for international markets, and adopting technology advances to achieve a high level of performance (Balakrishnan and Chakravarty 1996). On the other hand, ECM consumes considerable amount of resources, which in turn affects the lead time and productivity of regular NPD projects significantly. It also accounts for high EC costs with regards to manufacturing re-tooling costs, engineering rework, inventory obsolescence, and possible downstream EC propagation (Loch and Terwiesch 1999, Balakrishnan and Chakravarty 1996).

The objective of this research is to lay a foundation for modeling the ECM process within a multi-project product development environment and provide insightful decision-making suggestions for companies regarding how engineering changes should be implemented with minimal adverse effects on normal NPD activities in terms of key performance indicators, such as lead time and productivity. To be more specific, this research seeks to answer the following questions:

1. How important is ECM for a firm that is engaged in developing new products?
   - What are the fundamental characteristics of complex NPD and ECM processes? And what are the complex interactions between them?
   - Among these characteristics observed, what are the key contributors to the long lead time and low productivity for NPD in relation with ECM? And vice versa.

2. What is the optimal way of allocating limited resources between NPD and ECM?

The paper is organized as follows. In the next section, a brief review of literature with respect to the modeling method that previous research adopted is discussed. The methodology that this research used is then presented and justified. Section 3 presents the simulation model and the underlying assumptions. Model verification & validation, running results and decision-makng strategies are discussed in Section 4. In conclusion, limitations of and possible extensions to the current research are provided in Section 5.

2 METHODOLOGY

Papers associated with analytical or computer modeling of ECM or NPD in literature can be classified by three different types: mathematical model (analytical solution), concept framework, and computer simulation.

2.1 Literature Review

Formulating a mathematical model, which is to "represent a system in terms of logical and quantitative relationships that are then manipulated and changed to see how the model reacts, and thus how the system would react" (Law 2007), is one way to define and abstract the problem of interest. Among major algorithmic approaches, linear programming (e.g., Balakrishnan and Chakravarty 1996; Krishnan, Eppinger, and Whitney 1997; Barzizza, Caridi, and Cigolini 2001) is "to fit to solve the general problem of allocating limited resources among competing activities in the best possible way" (Hillier and Lieberman 2001). Another method that can be adopted is queueing theory (e.g., Dragut and Bertrand 2008) since the time wasted by waiting in lines for limited resources is a major contributor for both the long lead time and the low production rates of NPD and ECM. By applying appropriate queueing models using different types of probability distributions for inter-arrival and service times, average waiting time and number of entities in queue can be obtained to measure the performance of the queue.

The approach of concept framework was adopted by many researchers (e.g., Krishnan, Eppinger, and Whitney 1997; Loch and Terwiesch 1999; Browning, Fricke, and Negele 2006) for modeling product development process to support project planning and control.

To gain insights into the operation of a very complex and dynamic real world system without substantial simplification required for analytic models, computer simulation (e.g., Ho 1994; Ford and Sterman 1998; Browning and Eppinger 2002; Bhuiyan, Gerwin, and Thomson 2004; Cho and Eppinger 2005; Bhuiyan, Gregory, and Thomson 2006; Lévárdy and Browning 2009) is a very effective and powerful tool.

2.2 Methodology

This research adopts the "information flow" view of an NPD process (Krishinan, Eppinger, and Whitney 1997, Cho and Eppinger 2005). From this information processing standpoint, an NPD project can be treated as evolving product information that travels through time (total development cycle time) and space (all the departments involved) till the final design solution, consuming engineering capacity. However, we are not interested in the way how the input information of an NPD project evolves gradually into the eventual deliverable, but the discrete points in time when entities (i.e., NPD projects) arrive in and exit certain activities and the corresponding change of the state of system. By doing this, the duration of each NPD/ECM activity and utilization of resources from different departments will be captured. Also, the repeatable nature of an NPD process structure provides the validity for decomposing an NPD process into successive design and development phases, each enclosing several sequentially repeating activities. Nevertheless, NPD is an iterative process rather than a purely linear one, with unforeseen uncertainty and ambiguity (Terwiesch and Loch 1999). This feature can be represented by NPD iteration and random variation in activity durations.

3 MODEL FRAMEWORK

3.1 NPD Framework

Using the activity network as a fundamental framework (Bhuiyan, Gerwin, and Thomson 2004), the NPD model can be abstracted by three *phases* with certain degrees of overlapping, namely Concept, Design, and Production. Each phase consists of three sequentially numbered *activities* to represent its different stages. It is assumed that there is no overlapping among activities within each phase. That is, an NPD activity only receives final information from the upstream activity while an NPD phase is able to begin with preliminary information before the activities in the upstream phase are finished. *Figure 1* illustrates this 3-phase and 3-activity NPD framework.

3.1.1 Size and Frequency of NPD

It's assumed in this research that a company handles new NPD projects with a constant inter-arrival time; these inter-arrival times vary according to project sizes and product types. The reasons why these values were chosen are 1) from high to low, they represent three specified rates of arrival; 2) the smallest number was chosen so that companies that handle relatively simple but more frequent NPD projects start one NPD project each month while the largest number as 120 so that for the case of low arrival rate companies initiate more complex NPD projects every half year. When NPD arrives at a lower rate, we assume the project to be more complicated and thus require more processing time to finish. The duration of an activity is set to be proportional to the NPD project arrival rate.

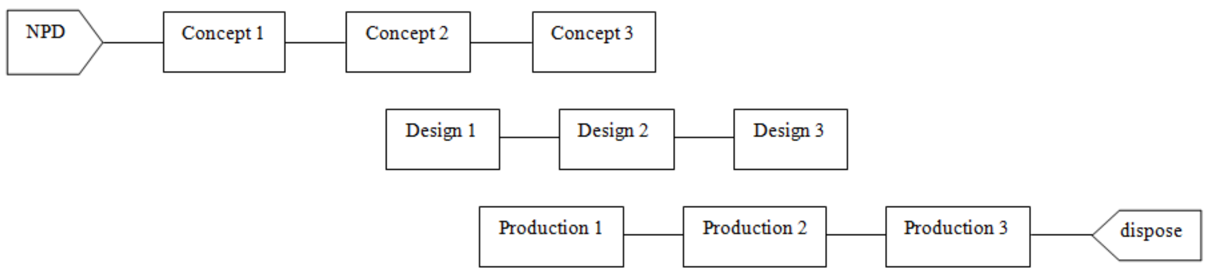

Figure 1: Three-phase & three-activity NPD framework

The activity duration is assumed to follow the normal distribution, which represents the uncertainties in product design and development processes. The mean value of activity duration within one phase remains the same, but increases as NPD entities proceed from one phase to another because of the increasing activity complexity since more product development tasks are involved. The sum of all the duration mean values (3 activities within 3 phases) for one entire NPD project is set to be equal to the inter-arrival value. This means that if everything is fixed without any uncertainty (i.e., there is no variation for activity duration and iteration), a company has the exact time to go through each NPD project without any overlapping. Detailed activity duration assignment is shown in *Table 1*.

Table 1: NPD Arrival Rates and Activity Duration

NPD Frequency	**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)

3.1.2 Overlapping

Overlapping is defined as the partial or full parallel execution of tasks (Bhuiyan, Gerwin, and Thomson 2004). By having this 3-phase and 3-activity framework, we are able to construct an NPD process with 0%, 33%, 66%, or a mixed (different ratio between phases) overlapping. The NPD process with 0% overlapping is also called a sequential NPD process. NPD process with 33% overlapping is the one with the first activity of the following phase starts simultaneously with the third activity of the preceding phase. For NPD process with 66% overlapping that is shown in *Figure 2*, the first activity of the following phase starts simultaneously with the second activity of the preceding phase.

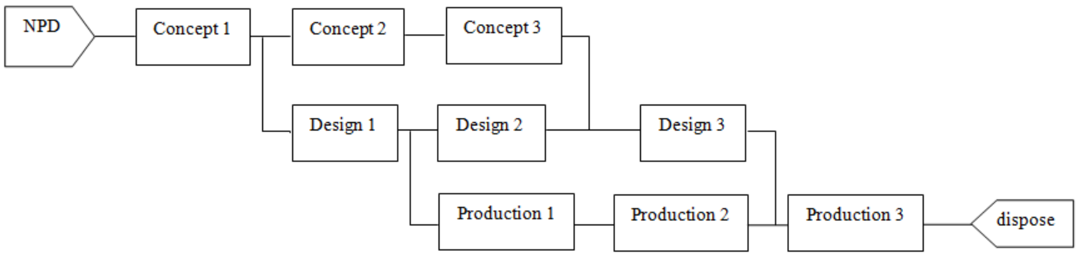

Figure 2: NPD Process with 66% Overlapping

3.1.3 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 but with less level of resource requirements.

By assuming that each NPD activity consumes a total number of 100 of resources to complete, 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 correspondingly.

3.1.4 Iteration

After each activity, there is a decision point where the NPD project either passes through or needs to go back for a rework by a pre-assigned probability. This iteration probability can be estimated based on experiences from previous projects. NPD projects may go back and repeat the just-finished activity or any of the previous activities, including activities in other upstream phases. This rework process is called *NPD Iteration* and is shown by *Figure 3*. If the new product information goes through the decision point after one activity, it means that the deliverable of this activity is a qualified input to the next. However, this does not guarantee that it won't cause any NPD iteration in later downstream activities. It's assumed that the probability of rework in recently completed activities is higher than those far upstream ones. Two levels of iteration probability, 10% and 20%, are examined in this research.

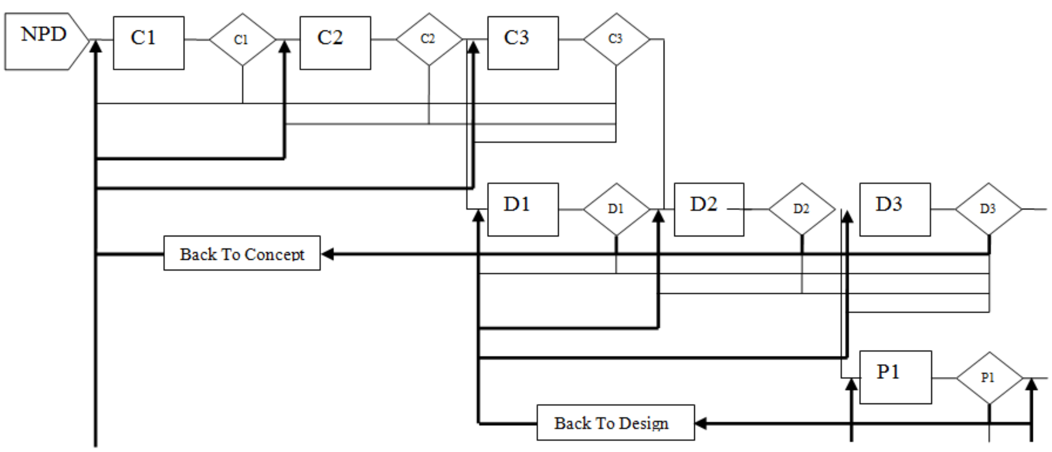

Figure 3: Model Overview of NPD with Overlapping and Iteration

3.2 ECM Framework

The ECM framework explores how changes made to a product component within the design and development process propagate to other components and later activities. EC propagation discussed in this paper is mainly caused by the following two facts: coupled product architecture and connected product development process.

3.2.1 EC Propagation due to Product Architectural Coupling

A complex product usually consists of several interrelated major systems, and each further contains interconnected subsystems, components, and elements. The interactions (e.g., spatial, energy, information, and material) (Pimmler and Eppinger 1993) occur between the functional and physical elements and will cause the EC to one element propagate to the other.

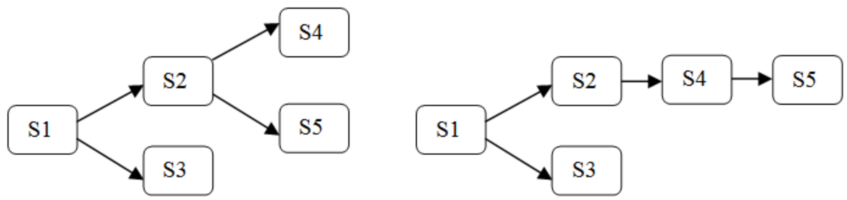

Figure 4: Interactions among Product Systems

Figure 4 shows two 5-system product configurations that are illustrated in this paper. For the 3 LevelOfSys (level of systems) product configuration shown on the left, system S1 on the top level is interrelated with two other systems, S2 and S3. It goes down only one level for S3 while systems S4 and S5 interact with S2. Changes to S1 will propagate to S2 and S3 and changes to S2 will propagate to S4 and S5. Since S3, S4 and S5 are at the bottom level, changes to them will not cause any propagation. It's assumed that during the EC propagation, changes to the children system(s) are triggered simultaneously by the completion of their parent. That is to say, when EC of S2 propagates to S4 and S5, changes to both systems will be implemented at the same time if there are enough resources available. The structure shown on the right in Figure 4 illustrates a 4 3 LevelOfSys configuration.

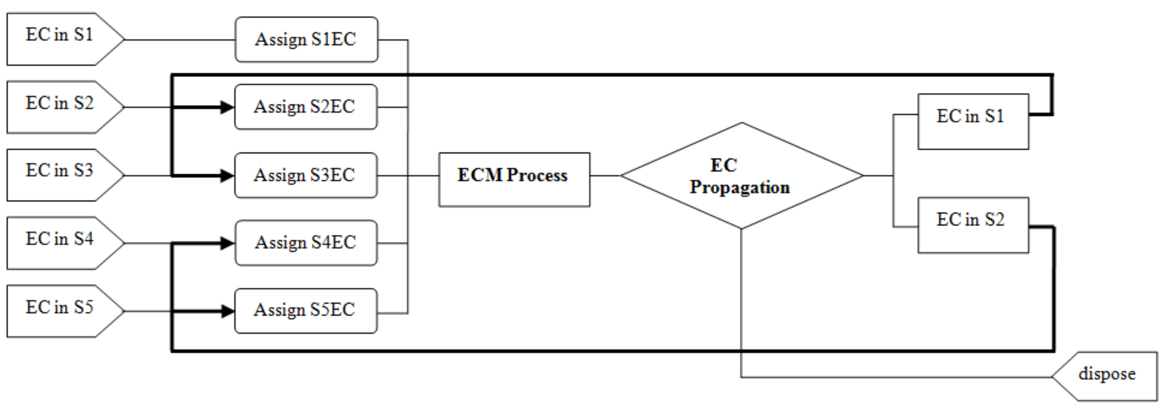

Figure 5: EC Propagation due to Connected Product Architecture at System Level

When an EC request is made to a company, it is classified by the product system in which this change is to be implemented. Then, the change is processed when there are enough resources available. During the ECM process, EC propagations may occur due to the fact that product systems interact with each other. As shown in Figure 5, after the implementation of one EC request on a certain product system (when this EC entity exits the "ECM process" sub-model), there is a decision module called "EC propagation" that checks whether there is any systems affected by this EC. If it is not on the bottom-level item, change will then propagate to its closest child system(s) by re-sending it to complete the whole ECM process again.

3.2.2 EC Propagation due to Development Process Coupling

Not only product architecture, but product development activities are also coupled. The feature that an EC may propagate to its later activities within the current phase or after is called *EC propagation based on work process.* For example, an EC that solves a design default may cause changes to later activities in design or production phase. This propagation phenomenon is modeled by adding decision points after each EC and then extending the change to its downstream activities by chance.Concept 3, three activities in Design, and three activities in Production each have an equal chance of implementing an EC. 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. Thus NPD ideas are less formally organized. Figure 6 shows the EC Propagation due to connected development process.

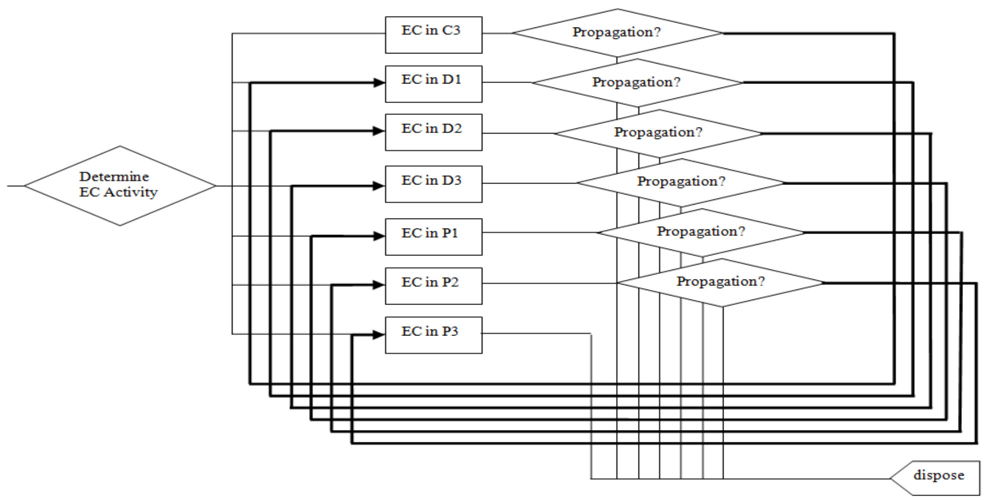

Figure 6: EC Propagation due to Connected Development Process

3.2.3 Size and Frequency of ECM

Compared with NPDs that are much more likely to stick to a planned schedule, ECs can occur without any plans. So we use exponential distribution to assume ECs' arrival. When EC arrives at a lower rate, the change is assumed to be more complicated and thus require more processing time to finish. The ECM process time is set to be proportional to its corresponding arrival rate just as NPD activity duration. It follows a triangular distribution, where there is a most-likely time with some variation on two sides, represented by the most likely, minimum, and maximum values respectively. 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 ECM within different NPD phases at three different arrival rates. We assume that each product system has an equal chance to receive an EC request.

Table 2: ECR Arrival Rates and Activity Duration

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)

3.2.4 ECM Effort

The amount of resources required for an EC to be processed is called *ECM Effort*. Two levels of ECM effort, High (10-10-10) and Low (5-5-5), 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.

3.3 Resource and Its Using Priority

Resources can represent staffs, computer/machine, documentation support, or any other individual server. It's assumed that each resource is qualified to handle all the NPD activities in three phases. When there are not enough resources available for both processes, resource using priority needs to be assigned to either NPD or ECM to seize necessary resource first.

3.4 Running Parameters

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

4 EXPERIMENTAL DESIGN AND RESULTS

4.1 Experimental Design

For the model described above, we analyzed the influence of 1) *Product Structure* (number of systems and level of systems); 2) *Process Structure* (NPD overlapping and iteration probability, and EC propagation due to the interactions among product architecture and development process); and 3) *Resource* (resource constraint – total number of resources available, resource using priority, NPD resource consumption – departmental interaction, and ECM resource consumption – ECM effort) on lead time and productivity under different NPD and ECM arrival rates and sizes. A separate application PAN (Process Analyzer) is used to evaluate the two performance measures for different scenarios. We examine three resources levels, 200, 100, or range (60, 80) numbers of resources from each department. 60 is the number of resources required for a major department at low level of departmental interaction to ensure that the major department has adequate amount to get NPD activities processed. After observing some preliminary results from the model, we find that the effect of resource constraint is significant when the number is less than 80. So we set the low level to be a range from 60 to 80 resources per department, increment by 10. Detailed values of model parameters are shown in *Table 4*.

Table 3: Summary of Model Parameters

Time Between Arrivals (NPD)	Constant 20 d	Constant 48 days	Constant 120 d
Time Between Arrivals (ECM)	Random (Expo) 12.5 d	Random (Expo) 25 d	Random (Expo) 50 d
Product Structure			
NoOfSys-LevelOfSys	5-3		5-4
Process Structure			
NPD Overlapping	0%	33%	66%
NPD Iteration Probability	*High:* 20%		*Low:* 10%
EC Propagation Probability	*High:* EC PP1 (15%) - EC PP2 (10%)		*Low:* EC PP1 (10%) - EC PP2 (5%)
Resources			
Total Number of Resources	(60, 80) increment by 5	100	200
Resource Using Priority	NPD High; ECM Low		NPD Low; ECM High
NPD Departmental Interaction	*High:* 40-30-30		*Low:* 60-20-20
ECM Effort	*High:* 10-10-10		*Low:* 5-5-5

4.2 Results

Only partial numerical results are presented in this paper due to space limitation. *Table 4* summarizes the parameter settings of the four charts shown in *Figure 7(a-d)*.

Table 4: Chart Description

	Arrival Rate	***Product Structure***	***Process Structure***		***Resource Using Priority***
			NPD Overlapping	NPD Iteration Probability	
Figure 8(a)	High		33%	10%	NPD High, ECM Low
Figure 8(b)		5-3			
Figure 8(c)		5-4			
Figure 8(d)		5-3		20%	

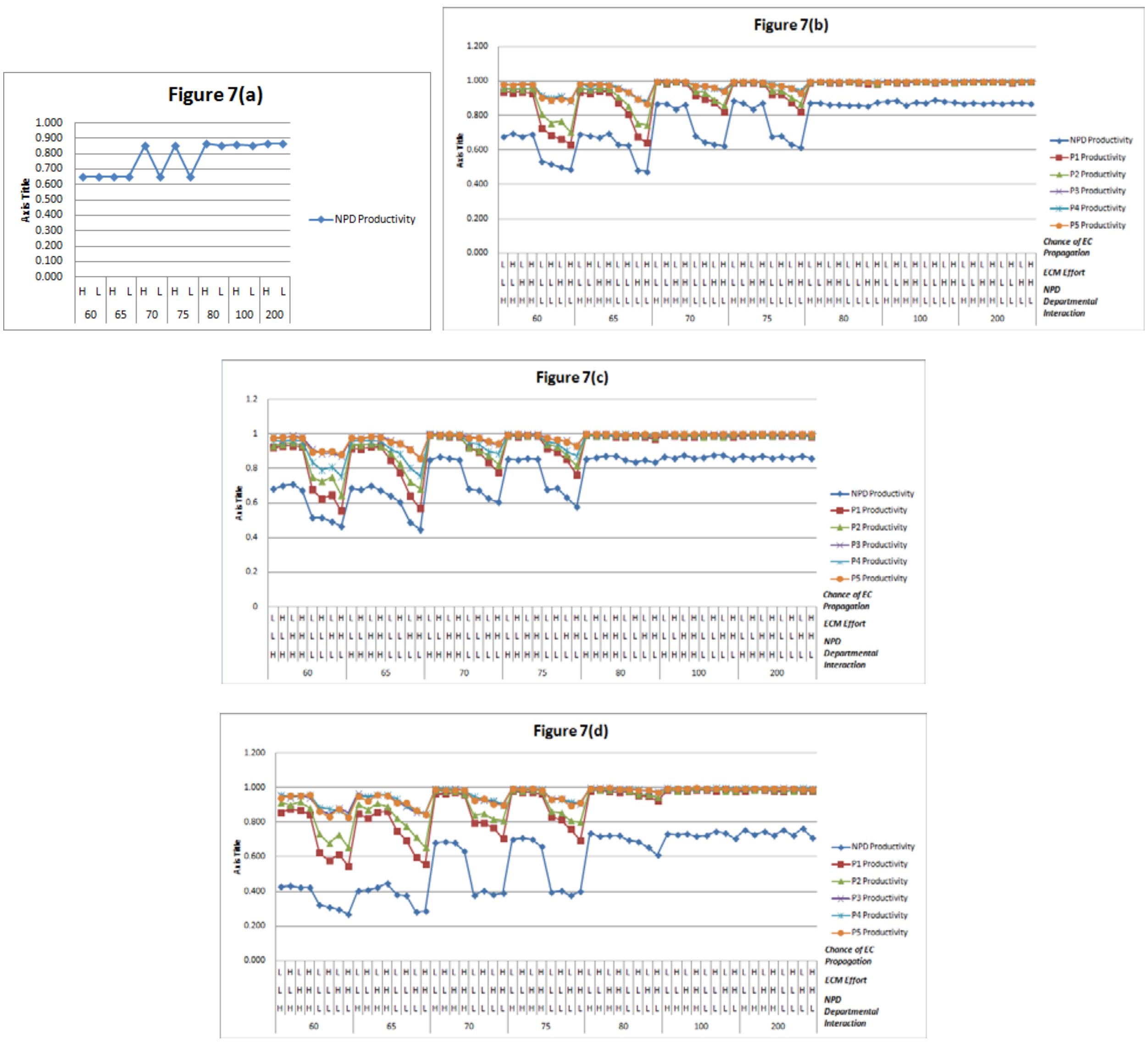

Figure 7(a-d): Productivity of NPD and ECM

4.3 Observations and Explanations

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

1. By comparing those scenarios with and without ECM, we find that the occurrence of ECs affects NPD productivity (as much as 24%) and lead time (as much as 44%) for a more coupled product structure (5-4 in this paper) when resources are limited and the departmental interaction is low.
2. When there are plenty of resources (200 resources/dept. in this paper) 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. However, this observation is under the assumption that NPD iteration probability doesn't increase with a higher overlapping ratio.
3. When there is limited number of resources (60-80 resources/dept. in this paper) for NPD and ECM activities, overlapping as much as possible is no longer recommended. If only limited resources are available, 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 because of concurrent execution of activities but longer wait time to obtain resources under higher degree of overlapping.
4. As the *Number of Resources* decreases, productivity of both NPD and ECM drops off, but NPD with a higher rate. When there are fewer resources available, the resource utilization raises, sometimes even gets close to 100%. 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 time in queue for fewer resources that are available.
5. Besides number of resources available, *Departmental Interaction* is the second important factor that influences the productivity and lead time of both NPD and ECM. 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.
6. 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.
7. 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 in the low departmental interaction case.

8. A greater *NPD Iteration Probability* causes a significant decrease in productivity of NPD and a slight decrease in productivity of ECM of high-level components when resource is limited and departmental interaction is low.
9. A more *coupled Product Structure* (where product systems are more interrelated with each other, higher value of LevelofSys in this paper) leads to a slightly lower productivity and a slightly higher lead time for NPD and ECM of high-level components. *Chance of EC Propagation* is not a major effect of low productivity and long lead time under the parameter setting in this paper. More investigation needed to explore these two model inputs' impact.

5 CONCLUSION

5.1 Main Contribution

The NPD and ECM model framework introduced above address several issues that previous research hasn't. In this model, we capture important NPD and ECM characteristics such as the iteration and overlapping of NPD process, interaction among different functional areas, and EC propagation due to product and process coupling. 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 turn affects the lead time and productivity of regular NPD activities significantly.
2. While each of the nine model variables, arrival rate, overlapping, NPD departmental interaction, ECM effort, resource constraints, resource using priority, NPD iteration probability, chance of EC propagation, and product structure affects the overall lead time and productivity of both NPD and ECM to some extent, the effect of resource constraints is most significant.
3. As stated, this model addresses decision-making suggestions for firms under different organization environment and resource constraint condition. Specifically, when the resources are limited, a medium level of overlapping and high departmental interaction is suggested to optimize system resource utilization.

5.2 Issues of the Model Application

First, the parameter setting and input data for this research are hypotheses based on relevant results from similar studies or the modeler's experience. These may be obsolete due to time concerns but still realistic when this simulation study was initiated. Second, this research is aimed at providing a model-based tool to evaluate the mutual influence of NPD and ECM. Given the model framework, companies may use different parameter setting according to their diverse development processes and different complexity levels of the products. However, determination of those model parameters requires not only sufficient knowledge of the product structure but also a thorough understanding of both NPD and ECM processes. Third, some model parameters, by their nature, are correlated with each other. For example, high *NPD Overlapping* means that more activities in the downstream phase start with information in a preliminary form, which will likely result in a high *NPD Iteration Probability*. At the same time, the added complexity of communicating and coordination resulting from a heavy weight multi-functional team (i.e., a high level of *NPD Departmental Interaction*) may also increase *NPD Iteration Probability* which is not exposed in this model version. Fourth, NPD and ECM performance has only been examined by a decomposed product structure in system level. Based on the extent to which a product or a process can be broken down and the knowledge of interfaces between elements, modeling complexity will grow exponentially.

5.3 Future Work

There are several aspects of this model that need further research.

- The current model deserves more investigations on its parameter setting and the dynamic influence among those model inputs.
- Besides lead time and productivity, other critical criteria such as cost and quality, can be used to review and evaluate the impact of ECM throughout NPD process.
- In the current model, probabilities for feedback iterations are assigned to an NPD project. However, when a new product project needs to go back to earlier NPD activities for 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.

REFERENCES

Balakrishnan, N., and A. K. Chakravarty. 1996. "Managing Engineering Change: Market Opportunities and Manufacturing Costs." *Production and Operations Management* 5 (4):335-356.

Barzizza, R., M. Caridi, and R. Cigolini. 2001. Engineering Change: A Theoretical Assessment and A Case Study. *Production Planning & Control* 12 (7):717-726.

Bhuiyan, N., D. Gerwin, and V. Thomson. 2004. "Simulation of the New Product Development Process for Performance Improvement." *Management Science* 50(12):1690-1703.

Bhuiyan, N., G. Gregory, and V. Thomson. 2006. "Engineering Change Request Management in a New Product Development Process." *European Journal of Innovation Management* 9(1):5-19.

Brown, S. L. 1995. "Product Development: Past Research, Present Findings, and Future Directions." *Academy of Management Review* 20(2): 343-378.

Browning, T. R., and S. D. Eppinger. 2002. "Modeling Impacts of Process Architecture on Cost and Schedule Risk in Product Development." *IEEE Transactions on Engineering Management* 49(4): 428-442.

Browning, T. R., E. Fricke, and H. Negele. 2006. "Key Concepts in Modeling Product Development Process." *Systems Engineering* 9(2): 104-128.

Browning, T. R., and R. V. Ramasesh. 2007. "A Survey of Activity Network-Based Process Models for Managing Product Development Projects." *J. Product Innovation Management* 16(2):160-172.

Cho, S. H., and S. D. Eppinger. 2005. "A Simulation-Based Process Model for Managing Complex Design Projects." *IEEE Transactions on Engineering Management* 52(3):316-328.

Dragut, A. B., and J. W. M. Bertrand. 2008. "A Representation Model for the Solving-Time." *European Journal of Operational Research* 189(3):1217-1233.

Eckert, C., P. J. Clarkson, and W. Zanker, 2004. "Change and Customisation in Complex Engineering Domains." *Research in Engineering Design* 15(1):1-21.

Ford, D. N., and J. D. Sterman. 1998. "Dynamic Modeling of Product Development Processes." *System Dynamics Review* 14(1):31-68.

Hillier, F. S., and G. J. Lieberman. 2001. *Simulation Modeling & Analysis*. 4th ed. New York: McGraw-Hill, Inc.

Ho, C. J. 1994. "Evaluating the Impact of Frequent Engineering Changes on MRP System Performance." *International Journal of Production Research* 32(3):619-641.

Huang, G. Q., and K. L. Mak. 1994. "Current Practices of Engineering Change Management in HK Manufacturing Industries." *International Journal of Operations & Production Management* 19(1):21-37.

Krishnan, V., S. D. Eppinger, and D. E. Whitney. 1997. "A Model-Based Framework to Overlap Product Development Activities." *Management Science* 43(4):437-451.

Law, A. M. 2007. *Simulation Modeling & Analysis*. 4th ed. New York: McGraw-Hill, Inc.

Lévárdy, V., and T. R. Browning, 2009. "An Adaptive Process Model to Support Product Development Project Management." *IEEE Transaction on Engineering Management* 56(4): 600-620.

Loch, C. H., and C. Terwiesch. 1999. "Accelerating the Process of Engineering Change Orders: Capacity and Congestion Effects." *J. Product Innovation Management* 16(2):145-159.

Pimmler, T. U., and S. D. Eppinger. 1994. "Integration Analysis of Product Decompositions." In *Proceedings of the ASME Design Theory and Methodology Conference*, 343–351. Minneapolis, Minnesota: American Society of Mechanical Engineers.

Terwiesch, C., and C. H. Loch. 1999. "Managing the Process of Engineering Change Orders: The Case of the Climate Control System in Automobile Development." *J. Product Innovation Management* 16(2):160-172.

AUTHOR BIOGRAPHIES

WEILIN LI is a Ph.D. candidate in the Department of Mechanical and Aerospace Engineering at Syracuse University, USA. She received the B.S. Degree in Mechanical Engineering and Automation from the School of Mechanical and Power Energy Engineering at Shanghai Jiao Tong University, China. Her research focuses on modeling and simulation of complex product design and development process, engineering change management, and process improvement to product realization. Her email is wli12@syr.edu

YOUNG B. MOON is on the Faculty of Mechanical and Aerospace Engineering at Syracuse University, USA. He is the Director of the Institute for Manufacturing Enterprises. He holds a PhD degree from Purdue University, USA and is a Professional Engineer (PE), a Certified Fellow in Production and Inventory Management (CFPIM) and a Certified Manufacturing Engineer (CMfgE). His professional interests include enterprise systems, product realization processes and systems, product life cycle management, and modeling and simulation. His email address is ybmoon@syr.edu.