2013

Modelling Engineering Change Management in a New Product Development Supply Chain

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International Journal of Production Research, 2013
http://dx.doi.org/10.1080/00207543.2013.807954

Modelling engineering change management in a new product development supply chain

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(*Received 4 August 2012; final version received 4 May 2013*)

The changes within a new product development (NPD) process are handled differently depending on the stage of the project. The changes during the initial stages of the project are addressed by design iterations, while the changes after the product design is complete are addressed using a formal engineering change management (ECM) process. The ECM process is a complex process, especially under a collaborative environment, where various independent entities work together for a common cause of product development. The interactions between the NPD and ECM processes have rarely been investigated in the research community. In this paper, we attempt to study the interactions between the various NPD and ECM process parameters by modelling the processes and simulated the model to understand the parameter interactions. The organisations in a supply chain have been characterised based on their interactions with the original equipment manufacturer (OEM) during the NPD process. The organisation process templates representing the NPD and ECM processes of each type of organisation in the supply chain have been modelled. The templates have been used to develop a simulation model representing the NPD and ECM processes for a supply chain. The process variables, such as processing rates, resources, resource composition, resource allocation priority, processing quality and phase overlap, have been included in the model. The results indicate that most of the variables and interactions among the variables have a significant influence on the NPD lead time. By identifying the status of the NPD process, the decision-makers can use these results to develop appropriate management policies to govern their product development projects.

Keywords: engineering changes; engineering change management; new product development; process simulation; system dynamics; supply chain

1. Introduction

Collaborative product development is becoming critical in addressing frequently changing customer needs and adopting rapidly evolving technologies. Original equipment manufacturers (OEMs) are collaborating (Shiau and Wee 2008) with various partners and suppliers who possess complementary capabilities in order to form a resource-rich extended organisation. To ensure successful product development in a collaborative manner, a systematic process (Ahmed and Kanike 2007; Cho and Eppinger 2005) for the new product development (NPD) process for such a new environment needs to be in place.

Generally, a NPD process consists of various phases (Nadia, Gatard, and Thomson 2006; Reddi and Moon 2011a; Reddi and Moon 2012) including concept development, detailed design, prototyping, production ramp-up and assembly and testing. While the project progresses, changes are inevitable but any changes have the potential of jeopardising the success of the whole project unless they are handled in a systematic manner. The manner in which the changes are managed depends on the status of the NPD project's progress. Assuming that the product is designed by the OEM and is manufactured by its suppliers, any changes occurring during the early stages such as the concept development and detailed design phases do not affect too many stakeholders (Shiau and Wee 2008), and are usually addressed by iterations in the NPD process. But those changes that need to be incorporated after product designs are finalised, i.e. after the detailed design phase, affect multiple stakeholders including suppliers, and customers. To distinguish such changes from those occurring during the normal NPD processes, the term 'engineering change' (EC) is used (Ahmed and Kanike 2007; Jarratt et al. 2011; Veldam and Alblas 2007). The ECM process typically consists of EC proposal, EC approval, EC implementation, and EC documentation phases. The ability to handle ECs effectively in any company engaged in product development enables them to become relatively more competitive (Barzizza, Caridi, and Cigolini 2001) in the market place by updating the product technologies, addressing design errors, accommodating changes in customer

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requirements, and improving product performance among others. Implementing ECs in a collaborative environment is a complex task (Veldam and Alblas 2007) as it involves various independently managed, regulated and owned organisations, but requires them to work for a common cause of product development.

When the interactions between the NPD and ECM processes occur under such a collaborative environment, understanding these interactions is a great asset to the OEM in managing the two processes effectively across the collaborative network. However, the interactions between the NPD and ECM processes have rarely been investigated in the research community (Jarratt et al. 2011; Reddi and Moon 2012). Since the ability to foresee the impact of the process managing strategies on the supply chain performance (measured by a NPD processing lead time) can also help avoiding any performance degrading issues, simulation models of the NPD and ECM processes can provide such necessary information to help foresee the supply chain performance under different conditions.

The system dynamics (SD) modelling methodology has been used to model and simulate complex systems (Sterman 2000). The SD methodology represents a system in the form of stocks, flows, time delays, variables and feedback loops. A 'stock' is analogous to a bathtub while 'flows' is its inlet and outlet. Stocks are connected by flows and the flows are defined by the system variables. During each simulation run, the difference between the inlet flow and outlet flow accumulates in the stock. At any point of time, the levels of all the stocks represent the state of the system. And the feedback loops are modelled using the information representing the systems' state to further influence the system variables that manage the system logic.

In this paper, we used enhanced versions of the templates for the OEM and suppliers developed by Reddi and Moon (2011a) in order to model a supply chain consisting of three types of suppliers and OEM. System dynamics simulation models (Forrester 1968; Sterman 2000) can be developed utilising the templates to study the interactions and dynamics of the ECM and NPD processes. The suppliers considered in this model are:

(i) The concept to design supplier (CDS) who participates in the concept development and detailed design phases of the NPD project.
(ii) The concept to manufacturing supplier (CMS), who participates in the concept development, detailed design, prototyping and production ramp-up phases of the NPD process.
(iii) The manufacturing supplier (MS), who participates in the prototyping and the production ramp-up phases of the NPD process.

The interactions between the OEM and the suppliers are modelled and simulated under various parameter settings representing different supply chain configurations. The effects of the considered parameters on the supply chain performance are studied.

The rest of the paper is organised as follows: Section 2 on the literature review reports the published research on tools developed to assist the ECM process. Section 3 describes the research methodology, where the enhancements to the templates developed by Reddi and Moon (2011a) are explained and the supply chain model logic is presented. In Section 4, results from the model simulation are presented followed by conclusions in Section 5.

2. Literature review

The literature on ECM is relatively limited (Jarratt et al. 2011) compared with other topics in the field of product life cycle management. Though much research on the NPD process is available, the interactions between the ECM and NPD processes have rarely been investigated. The research on ECs and ECM process has been concentrated on investigating the effects of ECs, proposing general framework to manage the ECM process within an organisation and across a supply chain, and developing tools to minimise the impact of EC propagation and assist in managing the ECM process.

The effect of ECs on MRP lot sizing (Chalmet, Bodt, and Wassenhove 1985) and manufacturing costs (Balakrishnan and Chakravarty 1996) have been investigated. Huge (1977), Frank (1980) and Diprima (1982) presented step-based procedures to plan and manage ECs to ensure acceptance by all departments and effective implementation. It was advised to categorise ECs based on criteria such as urgency, criticality, etc., so that they can be grouped and managed efficiently. Tavcar and Duhovnik (2005) proposed a generalised ECM process framework consisting of change request, change preparation, change approval, change of documentation and implementation in production. They suggested that, for effective planning and implementation of an EC, quality communication is required for the first three phases while clear definition of the EC is required for the last two phases.

A parameter-based workflow was proposed by Rouibah and Caskey 2003 to process and manage ECs. It was noted that engineers work with product parameters in the development of a product and hence capturing the relationships between them would form a network that further defines the workflow, when a particular parameter is changed due to an EC. Each parameter is associated with documents, defining it and personnel, managing it. In the case of an EC, the value of the parameter changes or needs revision, so the documents related to it are updated and associated personnel, are notified to re-evaluate their parameters if necessary.

Huang, Yee, and Mak (2001), Chen, Shir, and Shen (2002), Tavcar and Duhovnik (2006) and Lee, Ahn, and Kim (2006) presented a web-based workflow to process ECs across the supply chain. Huang, Yee, and Mak (2001) proposed server client architecture to support the ECM process functions, EC proposal, documentation, evaluation and notification, while Chen, Shir, and Shen (2002) and Tavcar and Duhovnik (2006) used a wide area network (WAN) connecting all the product data management/product lifecycle management (PDM/PLM) systems/servers of the suppliers to the server/(PDM/PLM) system of the OEM/lead enterprise, to administer the ECM process in a distributed environment. Lee, Ahn, and Kim (2006) presented a framework that captured the tacit knowledge from the formal and informal communication between the collaborating organisations using the knowledge management techniques. This captured knowledge was later put into context with the help of semantic web technology to assist the decision makers at appropriate phases of the ECM process. Reddi and Moon (2011b) proposed a framework for ECM process in a collaborative environment based on service oriented architecture. This framework has all the advantages of the web-based frameworks and additionally enhances the agility of the ECM process. This framework enables the suppliers to have their own ECM process workflow, while collaborating with the OEM.

The tools developed to help manage and assist in the planning and implementation of the ECM process include a variety of design structure matrices, change propagation tools, virtual reality (VR) technology based tools and ECM process simulation models. The basic design structure matrix (Browning 2001) captures the dependencies between the system components so that the propagation of change in one system component can be propagated easily across the system. A combined product risk matrix proposed by Clarkson and Eckert (2001), Clarkson, Simons, and Eckert (2004), Jarratt (2004) and Keller, Eckert, and Clarkson (2005) portrayed dependencies of all system elements, making it possible to visualise the vulnerability of system components with respect to changes in other components. A change impact matrix relating the product features to production elements was developed by Aurich and Martin (2007) in order to group the ECs for processing and planning the implementation. Ollinger and Stahovich (2004) developed a computer program called *RedesignIT* that can identify the impact of a change in terms of the possible or certain effected factors and also make suggestions to address the effects. Reddi and Moon (2009) proposed a framework to manage the engineering change propagation using the object-oriented programming concepts. Two input screens' interfaces were developed to access the tool, one input screen was used to capture the tacit knowledge of dependencies between component features during the systems engineering and design phases of the NPD project, while the second screen was used to generate a list of affected component features, after providing the EC information. Assuming that an EC is approved and is sent to manufacturing for implementation, Barzizza, Caridi, and Cigolini (2001) developed a mathematical model that would suggest a time for implementation of the EC to ensure minimum impact of the EC.

In addition to the tools for assisting decision makers with the ECM process, simulation models of the ECM and NPD processes have been developed by a few researchers to understand the process dynamics and assist in the decision-making process of the ECM. Chalmet, Bodt, and Wassenhove (1985) developed a mathematical model of a firm aiming at reducing the inventory losses due to an EC. The effects of ECs on production lot sizing have been studied assuming that EC makes the inventory of products obsolete. Nadia, Gatard, and Thomson (2006) developed and simulated the engineering change request (ECR) process in the NPD process to conclude that processing of ECs in batches is advantageous compared with processing immediately as the ECs are being requested. Li and Moon (2009) studied the interactions between the NPD and ECM process using discrete event simulation methodology.

Repenning (2000) developed a model of a multi-project NPD process and successfully illustrated the phenomenon of fire fighting in an organisation due to changes in the later phases of the NPD process. The NPD project was modelled as a set of tasks, and the existence of the fire-fighting phenomenon in the present NPD executing industries was demonstrated. To study the dynamics of the process, an increased number of tasks were introduced at a particular time during the simulation. It was concluded that until a certain magnitude of increase in the number of tasks (tipping point), the system returns to its normal performance level after a brief period of underperformance immediately following the period when the higher number of tasks was introduced. Beyond the tipping point, the system would remain in an undesirable steady state of underperformance, leading to a vicious cycle of sudden demand for resources before the product launches.

Black and Repenning (2001) presented an advanced version of the model presented by Repenning (2000) to investigate the policies that a manager should adopt in order to counter or avoid the fire-fighting phenomenon. The implementation of the model presented by Repenning (2000) to study the potential dynamics of the NPD process of an electronics manufacturing organisation was described. The NPD project was modelled as a group of parts that exist in any of the following four states:

(i) parts to be designed,
(ii) prototyped parts,
(iii) tested parts, and
(iv) revised parts.

The resources assumed were of a single type – ‘engineers’ thereby ignoring the specialisations and the fact that varying demand for specific resources (such as design, production, marketing, etc.) exists throughout various phases of the NPD process. It was concluded that the combination of multi-project dynamics and human psychology are leading to the fire-fighting in a NPD process. Allocation of resources to current projects ahead of the future projects is leading to a vicious cycle of huge demand for resources in later part of the projects (Repenning 2001; Black and Repenning 2001).

System dynamics and cybernetics (Rodrigues, Dharmaraj, and Rao 2006) are used to model the change management in NPD project. The model is classified into three sectors: project workflow sector, competent project staff sector, and project staff salary and revenue sector. The NPD project is described by three stocks, namely, ‘work to be done’, ‘work in progress’, and ‘work finished’. Work flow between these stocks is determined by the productivity of the available competent project staff. The work that failed to meet the requirement is sent back to the ‘work in progress’ stock via ‘rework’ stock. Likewise the model also includes the recruitment and training of the project staff along with the cost perspective of the NPD project.

Though the simulation models represent the NPD process and changes within the process, the main drawback of these simulation models is that they do not consider the ECM process as a formal process and fail to acknowledge the phases of the ECM process. They also do not consider the phases within the NPD and the flow of work between those phases. Identifying the phases within the process is vital, as it helps to understand the work flow along with the process dynamics by identifying the leverage points of the process. A manufacturing organisation consists of various functional departments and, in most cases, the different phases within the product development process are controlled by different departments. For example, the prototyping and production ramp-up are planned and controlled by the production department while the concept and design phases are planned and controlled by the design departments. Consideration of the phases within the processes would also help model interactions between these processes, which would further facilitate realistic modelling of the process and management policies. As it appears, better process modelling would enable superior understanding of the process dynamics and accurate estimation of the impact of the management policies like resource allocation, batch processing etc.

The ECM process in a collaborative environment evidently has never been modelled. The interactions between the suppliers and the OEM have also not been modelled and the effect of suppliers ECM process parameters on the OEM performance is not studied. Addressing this gap, Reddi and Moon (2011a) used system dynamics methodology to model and simulate the interactions between the NPD and ECM processes. They proposed the NPD and ECM processes templates for organisations based on the observation that suppliers interact with OEM organisations at specific points in the NPD process. These templates facilitate easy modelling of the processes across the supply chain by assembling the appropriate organisation templates that represent the suppliers based on their degree of participation in the NPD process of the OEM.

3. Research methodology

Although it seems evident that discrete event simulation is well suited to model the problem by considering the ECs as discrete entities that are processed by various resources (Li and Moon 2009), we have adopted the system dynamics methodology for the following reasons. The number of ECs within a products’ life cycle are considerably large (Jarratt 2004; Langer et al. 2012), in the order of thousands in high technology products such as aircraft and automobiles, and modelling them using discrete event modelling methodologies would be complex and result in large amounts of data tracking the flow of each entity. Modelling them as flows would considerably decrease the amount of data resulting from the model simulation and would be effective in studying the effect of policies adopted to process ECs. Noting that the system dynamics methodology has been effectively adopted by Black and Repenning (2001) to model the changes within a NPD process, we have adopted a similar approach in modelling the ECM process.

The initial templates (Reddi and Moon 2011a) were of basic detail and were only good enough to demonstrate the advantages of the developed templates. The modelled templates did not include the phases within ECM process, resource allocation priority, and capability to model the batch processing of ECs. This paper presents a supply chain model developed by using the enhanced versions of these templates proposed by Reddi and Moon (2011a). The enhanced templates include the provisions for prioritising the resource allocation to the phases of the NPD and ECM phases, grouping the ECs for processing and the phases within the ECM process.

3.1 *Enhanced templates*

In a collaborative product development setting, the suppliers interact with OEMs at specific stages during the NPD process. Having discerned typical patterns of the interactions, several templates for all the organisations in the supply chain have been developed by Reddi and Moon (2011a). Since then, the templates have been enhanced to include additional phases of the ECM process, EC grouping, and prioritised resource allocation to the phases of NPD. The enhanced templates are used to model a supply chain consisting of one OEM and three types of suppliers: Concept to design supplier (CDS), concept to manufacturing supplier (CMS) and manufacturing supplier (MS).

The ECM process that was modelled as single phase in the previous research (Reddi and Moon 2011a) has been expanded and modelled by including EC proposal, EC approval, EC implementation and EC documentation phases. The capability of processing ECs in batches has been embedded in the enhanced templates. The size of the batches can be defined during the simulation set up; a value of zero indicates that the ECs are processed immediately while a non-zero value indicates the batch size. During the project execution the ECs are only processed in groups and are delayed until a group size is equal or greater than the indicated EC batch size. But in the final stages of the project, when the ECs are proposed infrequently, they are processed immediately upon proposal to avoid any unnecessary delay. The status of the project is defined by the percentage of components processed in the production-ramp up phase. The order in which the resources are allocated to the phases of the NPD and ECM processes can be changed and are not fixed.

In addition to the above improvements, the resources, which were assumed to be infinite by Reddi and Moon (2011a) to ensure the completion of the NPD project within a year, are considered to be limited. To coordinate with limited number of resources, the phase overlap is changed from a time-based parameter to a project-status-based parameter. The phase overlap was defined by Reddi and Moon (2011a) in terms of the time delay, i.e. the time after which a phase starts following the start of the previous phase. In the enhanced templates, the phase overlap is defined in terms of the number of components processed in the previous phase instead of the time, the details of which are presented in the following model logic (Section 3.2). These changes attempt to address the limitations of the organisation templates proposed by Reddi and Moon (2011a) by increasing the functionality and eliminating the impractical assumptions like unlimited resources. Assuming limited resources makes it necessary to include additional functionality like resource allocation options available. These changes as a whole bring the model closer to reality because organisations usually have limited resources and always need the flexibility in allocating resources to address long term and short term goals.

3.2 *Model logic*

The NPD project starts with an OEM determining the number of components constituting the NPD project and the percentage of the components to be handled by each of the suppliers. The components are then transferred to organisations designing the corresponding components. The components concepts are developed and followed by the detailed designs. The detailed designs from the CDS are transferred to the OEM, from where the detailed designs are again transferred to the MS and OEM for prototyping. After the prototyping, the components are sent from the CMS and MS to the OEM for prototype assembly and testing. The prototype assembly and testing are considered complete when all the components of the project are prototyped and transferred to the OEM for assembly and testing. Once the prototype assembly and testing is complete, appropriate proportions of the prototypes defined by the percentage of components manufactured by the organisations are transferred to the OEM, MS and CMS for production ramp-up. The produced components are then transferred to the OEM for product assembly and testing. The assembled and tested products are then considered, ready for market release. The entire NPD project is considered complete when all the components are ready for market release. Figure 1 shows the schematic of the simulation model logic.

The process characteristics such as resources, resource composition, phase overlap, processing quality, processing rate, allocation priority, out sourcing, change propagation and EC grouping have been considered and simulated to study their effect on the OEM performance.

3.2.1 *Resources and resource composition*

The components at each phase are processed by shared resources as well as dedicated resources. The examples of the dedicated resources are the design resources, production resources, quality and testing resources, and marketing resources. The shared resources examples are design and production resources and production and quality resources. While the dedicated resources are allocated to address the respective demands, the shared resources are dynamically allocated to address the demand for any one of the dedicated resources. The design and production resources are allocated to meet the demand for design or production resources, while the production and quality resources are used to

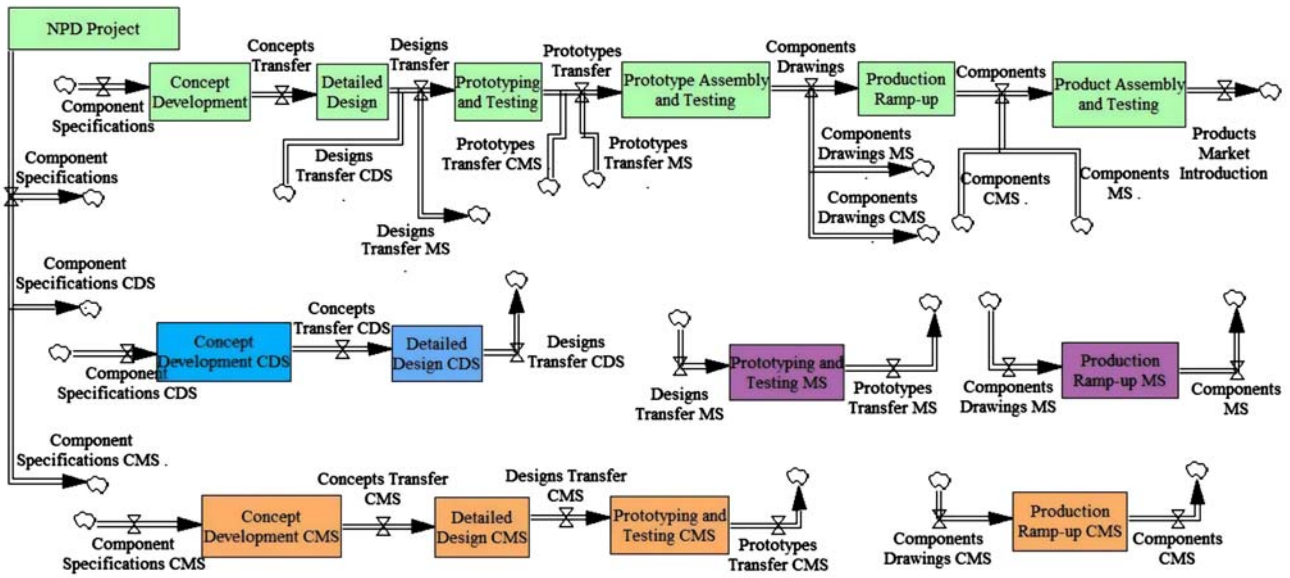

Figure 1. Schematic diagram of the supply chain model interactions.

meet the demand for production or quality and testing resources. An example of the resource composition values used in the model simulation corresponding to the levels high dedicated and high shared can be found in Table 1.

3.2.2 *Phase overlap*

The phase overlap represents the percentage of overlapping between the NPD phases and expressed in terms of the components processed by the previous phase. For a given percentage of phase overlap P, processing at any phase starts when the (100-P) percentage of NPD project components are processed at the previous phase. For example, for a phase overlap of 75% the design phase starts when 25% of the component concepts are developed. This indicates an overlap of 75% between the design and concept phases. Similarly for 0% phase overlap the design phase only starts when 100% of component concepts are developed in the concept phase.

3.2.3 *Processing quality*

At each phase as the components are processed, only a percentage of the processed components, representing defect/error free components are considered ready for the next processing phase. While the other proportion of the components considered defective are either looped back to the previous phases for reprocessing or processed using the ECM process. For example, at the end of the concept phase, all the defective components are fed back for concept reprocessing, while at the end of the detailed design phase, the defective designs are either sent to the concept phase or detailed design phase for reprocessing. The components that require reprocessing after and during the prototyping and testing phase of NPD process are processed through a formal ECM process. The number of changes processed by any organisation is the product of total number of changes and percentage of NPD project components handled by the organisation.

Table 1. Resource composition.

	Resource type					
	Design resource type	Production resource type	Quality and testing resource type	Marketing resource type	Design and production resource type	Production and quality resource type
High dedicated	0.30	0.30	0.1	0.1	0.10	0.10
High shared	0.15	0.15	0.1	0.1	0.25	0.25

Table 2. Processing quality data.

	NPD phases				
	Concept development	Detailed design	Prototyping	Production ramp-up	Assembly and testing
High	0.90	0.95	0.05	0.03	0.02
High-medium	0.85	0.90	0.10	0.06	0.04
Medium	0.80	0.85	0.15	0.10	0.05
Medium-low	0.75	0.80	0.20	0.15	0.10
Low	0.70	0.75	0.25	0.20	0.15

Note: NPD, new product development.

The processing quality in the concept and detailed design phases is defined by the percentage of error-free concepts or designs developed. And the processing quality in the prototyping and testing, production ramp-up, and assembly and testing phases, is defined by the percentage of processed components effected by proposed ECs. A range of realistic values (Ahmed and Kanike 2007; Langer et al. 2012; Reddi 2011; Reddi and Moon 2012) are assumed to simulate the model so that the effects of the processing quality, and its interactions with other values, on the NPD lead time can be studied.

3.2.4 *Processing Rate*

Each organisation has a desirable processing rate, which would be the actual processing rate if available resources were sufficient. If the resources are not sufficient, the processing rate is adjusted based on the available number of resources. At a certain interval (such as weekly), the number of resources required to attain the desired processing rate is calculated based on the components to resource type ratios. The components to resource type ratios define the number of components a single resource of any resource type can process within the simulation time unit. If the available resources are greater than the required resources, the desired processing rate is the actual processing rate. Otherwise, it is calculated from the available resources and the components to resource ratios.

3.2.5 *Resource allocation priority*

The order in which the resources are allocated to the different phases of NPD and ECM processes is defined by the allocation priority. An integer (between 1 to 9, since the number of the total NPD and ECM phases is 9) is assigned to each of the phases that indicate the order of resource allocation. The higher the number, the higher its priority. In other words, the phase with integer value of 9 is first allocated with resources while the phase with integer value of 1 is allocated resources last.

During resource allocation, the dedicated resources are first allocated to address the demand for resources, followed by the shared resources. After the allocation of dedicated resources, the design and production resources are allocated to address the demand for design resources followed by production resources. In the next stage, the production and quality resources are allocated to address the demand for production resources followed by the demand for quality and testing resources. The priority of each phase corresponding to the ECM, NPD and combination priority conditions can be found in Table 3.

Table 3. Allocation priority.

	Phases								
	New product development					Engineering change management			
Priority	Concept	Design	Prototyping	Production	Assembly	EC proposal	EC approval	EC implementation	EC documentation
NPD	9	8	7	6	5	4	3	2	1
ECM	5	4	3	2	1	9	8	7	6
Combo	9	8	7	2	1	6	5	4	3

Notes: EC, engineering change; ECM, engineering change management; NPD, new product development.

3.2.6 *Outsourcing*

The outsourcing is defined as a percentage of NPD project components that are processed by suppliers. The percentage of outsourcing is the sum of the percentages of components handled by all the suppliers (CDS, CMS and MS in this case) expressed as percentage of the components constituting the NPD project.

3.2.7 *EC grouping*

The organisation may adopt various strategies to process the components affected by ECs depending upon the available resources and time. It may process the components as they are proposed to ensure least possible time or can group them then process in batches to ensure better resource utilisation and productivity. An EC batch size of 0 indicates that the components are processed as soon as they are proposed, and any value other than zero indicates the minimum batch size or components queue required to be processed. As long as the number of components waiting to be processed via ECM is less than the minimum batch size, the components are not processed.

3.2.8 *EC propagation*

When an EC is proposed, it would generally affect multiple components due to change propagation. To address this phenomenon in the ECM process, all approved ECs are multiplied with an EC propagation index. The index of one or higher indicates that multiple components are being affected by a single EC. The value of the EC propagation index depends upon the NPD project status. The status of the project is indicated by the number of components manufactured, signifying the completion of the project. The greater the number of manufactured components is, the greater the value of the propagation index is. The values of the EC propagation index for 25%, 50% and 75% project completion are 1.2, 1.4 and 1.6 respectively.

4. Model verification and validation

The core assumptions noted in developing the templates have been verified using an industry survey (Reddi 2011). The survey consisting of 24 questions was given to employees of manufacture-to-order companies who collaborate with suppliers playing the role of the OEM. These surveyed companies include the companies that design and manufacture pressure vessels and build ships to order. The questions were designed to estimate the values of various parameters required and assumed to be known in this research. For example, the surveyed engineers were asked to provide an estimate for the percentage of components that would need rework after the design is released to manufacturing.

The phases within the NPD process were affirmed by 80% of the survey respondents. The NPD phases include concept development, detailed design, prototyping and testing, production ramp-up and product assembly and testing. Ninety-five per cent of the respondents agreed that they would divide the NPD project into independently workable parts that would later be assembled together to complete the project. The categorisation of the suppliers based on their involvement in the NPD process was approved by about 95% of the survey respondents.

While 45% of the respondents agreed that a formal engineering change management process is in place to guide personnel with engineering changes, 55% did not agree that a formal engineering change process occurs. Notwithstanding, all the respondents have indicated that product data are not modified without being reviewed by all the personnel associated with the product data. This indicates that although a formal ECM process is being adopted, it is not recognised and practised as a formal change management process.

The OEM template used to develop the other organisation templates has been verified by gradual addition of features and reviewing the results for consistency at each addition. The OEM template that is the base template (from which the supplier templates have been generated by modifying the NPD phases) has been validated using the data from the previous work presented by Repenning (2000) and Black and Repenning (2001).

Black and Repenning (2000) spent 3 months in a midsize manufacturing company interviewing the personnel and observing the day-to-day product development activities to provide an assessment of the product development process. This included 33 interviews with 10 project teams and 15 process teams from six facilities. The participants represented all the departments within the organisation including marketing, cost accounting, design and manufacturing and assembly. It was noted by the research programme manager that the critical issues in the product development projects constantly surfaced in the last months before the scheduled market introduction, in spite of increased engineering staff and managerial attention.

The data collected included the 'problem logs' from the development processes over the years until model year 1998. It was observed that the company identified problems in new products in later stages rather than early stages. As the project launch neared, the unresolved problem accumulated and engaged resources working on other projects scheduled for later launch. This pattern appeared to be never ending, as the same pattern was observed at the launch of all its products irrespective of the increase in engineering resources and managerial supervision as noted earlier. The company had a single milestone, for the entire product development process, which is the ultimate product launch.

The authors developed a model to investigate the role of the testing and prototyping on the ongoing overall product development activities in the organisation. The model was later simulated for 13 model years and the pattern of fire-fighting (Black and Repenning 2001) which was implied from the collected data was observed.

The NPD and ECM processes of the OEM were modified to emulate the models presented by Repenning (2001), Repenning (2000) and Black and Repenning (2001). The modifications done to the OEM template to imitate the model presented include:

(i) It is assumed that the changes are only in the individual components and not in the product assembly. This means that the change request probability in the assembly and testing phase is zero. ECs are proposed at the end of prototyping and testing phase and during the production phases only.
(ii) The NPD phases concept, design, and prototyping are assumed to represent the 'early phase', while the production, assembly and testing and ECM are assumed to represent the 'current phase' in Repenning's model (Repenning 2000). The EC documentation phase has been side-lined. The phases of EC proposal, EM approval and EC implementation of the ECM process have been assumed as a single phase instead of the three phases.
(iii) The number of changes in the early (concept and design) phase is one third of that in the current stage (production and assembly).
(iv) At the end of each year components are transferred from early phase to current phase, while the components from current phase are thereafter released into the market.
(v) A NPD project constituting of a definite number of components is started every year and another NPD project is completed and released to the market.

The model was simulated for the duration of 13 years, with one time increase in the number of components constituting the NPD project, in the third year. The increase in the number of components was defined as a fraction of the components in the base case (1000 components). The value of the fraction is increased from 0 to 1 with increments of 0.1, where 0 represents the base case of 1000 components and 1 indicates 2000 components. The performance was measured as 'quality' – defined as the number of components processed divided by the number of components in the NPD project.

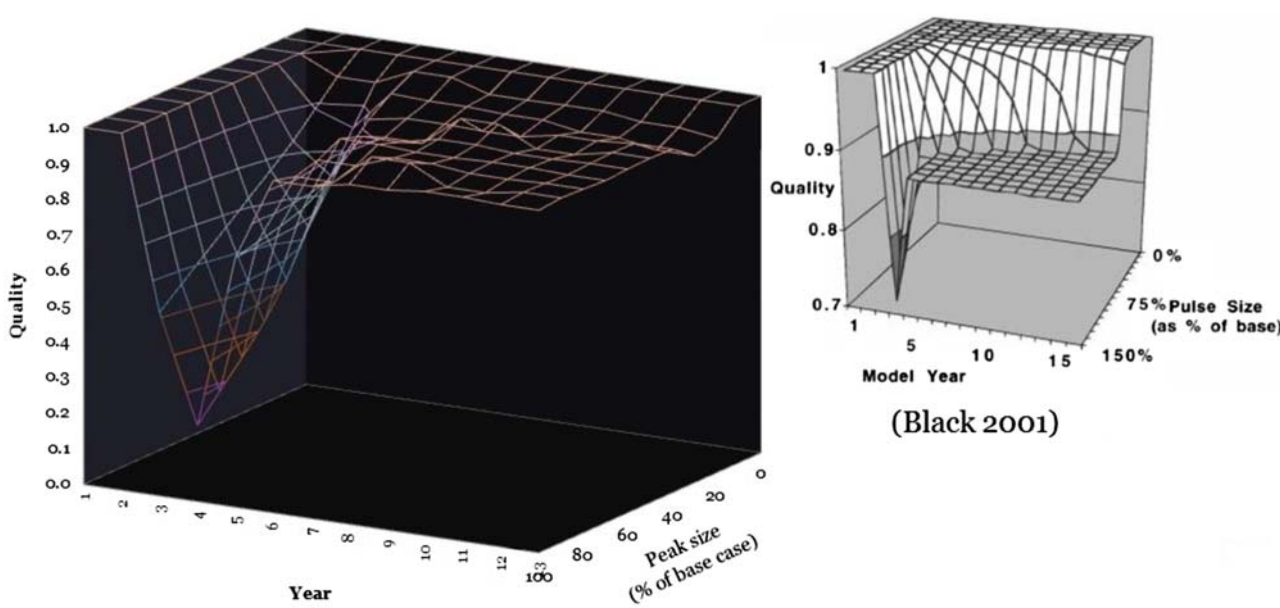

Figure 2. Validation of the simulation model comparing it with previous research by Black (2001).

Figure 2 shows the performance of the NPD process as a percentage of unprocessed components which is defined as the difference (1-quality) multiplied by 100. The system performance for a period of 13 years and various magnitudes of test peaks varying from 0 to 1 have been, consequently, recorded and plotted. For test peaks 0.1 and 0.2 the performance of the process, plummets after the peak is introduced, but recovers to its normal state of performance over the next couple of years. But for all the test peaks from 0.3 to 1, the system performance falls immediately after the peak is introduced and the system recovers to a steady state of performance that is below the normal state of performance. This condition would drastically increase the demand for resources just before the product launch so as to make it possible to get the system back to normal state of performance. This would repeat annually and such a condition is called fire-fighting (Black and Repenning 2001; Repenning 2000).

5. Results

The system dynamics model of NPD and ECM processes has been simulated to study the effects of the process parameters on NPD lead time. The processing of a NPD project consisting of 1000 components is simulated. The duration of the simulation was set to ensure all the components are processed and are ready for market introduction. The period of time from the time the NPD is initiated to the time when all the components are ready for market introduction is defined as NPD lead time. The NPD lead time is considered to be a measure of process performance and the effect of all system parameters and their interactions on the lead time are studied. The simulations were carried out in three cases aiming to study the effect of different process parameters on the NPD lead time. Case 1 studies the effect of all the parameters on

Table 4. The 31 variables representing the ECM and NPD process across the supply chain.

Process parameters		Low	High
Original equipment manufacturer process parameters	EC batch size	40	0
	Processing quality	High	Low
	ECM processing rates	50	10
	Processing rate	100	20
	Phase overlap	100	0
	Resources	200	40
	Resources composition	HD	HS
	Allocation priority	ECM	NPD
	Per cent out sourced	70	30
Concept to manufacturing supplier process parameters	EC batch size CMS	40	0
	Processing quality CMS	High	Low
	ECM processing rates CMS	50	10
	Processing rate CMS	100	20
	Phase overlap CMS	100	0
	Resources CMS	200	40
	Allocation priority CMS	ECM	NPD
	Resources composition CMS	HD	HS
Manufacturing supplier process parameters	EC batch size MS	40	0
	Processing quality MS	High	Low
	ECM processing rates MS	50	10
	Processing rate MS	100	20
	Phase overlap MS	100	0
	Resources MS	200	40
	Resources composition MS	HD	HS
	Allocation priority MS	ECM	NPD
Concept to design supplier process parameters	Processing quality CDS	High	Low
	Processing rate CDS	100	20
	Phase overlap CDS	100	0
	Resources CDS	200	40
	Allocation priority CDS	ECM	NPD
	Resources composition CDS	HD	HS

Notes: CDS, concept to design supplier; CMS, concept to manufacturing supplier; EC, engineering change; ECM, engineering change management; HD, high dedicated; HS, high shared; MS, manufacturing supplier; NPD, new product development.

the NPD lead time, while Case 2 concentrates on 13 parameters representing the interactions between the OEM and its suppliers. Case 3 studies the effect of each of the 13 parameters considered in Case 2 after keeping all the other parameters constant at low and high levels. The details of the simulations set up, and results are discussed below.

Case 1: For this case 31 process parameters were considered with two levels, high and low. The values of the model factors or variables corresponding to these two levels used in the simulation can found in Table 4. Factorial design from the design of experiments (DOE) (Antony 2003) methodology was used to generate the simulation input parameter data and analyse the model results.

The graphs showing the effect of each factor on the lead time are shown in Figure 3. The effects plots of all factors have a non-zero slope indicating that all the factors affect the NPD lead time. The factors such as resources, processing quality, allocation priority and percentage of outsourced components effect the NPD lead time to a greater extent while the rest of the factors have relatively smaller effect in the NPD lead time.

Case 2: Using the factorial method of DOE, the effects of the 13 variables, representing the interactions between the OEM and suppliers, are studied at two levels. The exact values of the 13 variables used in the simulation can be found in Table 4. Keeping the values of all the system parameters at low and high values the model was simulated using the generated simulation input data for 13 selected parameters. The simulation results were later analysed using the factorial design methodology of DOE. The Pareto graphs in Figures 3 and 4 show the effect of each process parameter on the lead time. It is observed that the number of factors effecting and extent of their effect on NPD lead time varies, based upon the state of the other variables which are set constant at one of the two levels low and high. When the factors (refer to Figure 4) are kept constant at level high, processing rate is the only factor that has significant effect. But, when the factors are kept at level low (Figure 5), the processing rate (G) and allocation priority (L) have significant influence on the NPD lead time, while processing rate MS shows relatively smaller influence. The EC batch size which had a noticeable influence on the NPD lead time when the parameters were set constant at high, does not demonstrate any effect on the NPD lead time when the variables are kept constant at level low, indicating the existence of an interaction. This indicates that the EC batch size should correspond to the processing capacity and thus the available resources. Setting large EC batch size keeps the resources idle or away from addressing the ECs in time to avoid delays, waiting for the batch size number of ECs to accumulate. And in the same manner setting a small batch size frequently keeps the personnel away from other development projects that would result in worse performance (Black and Repenning 2001).

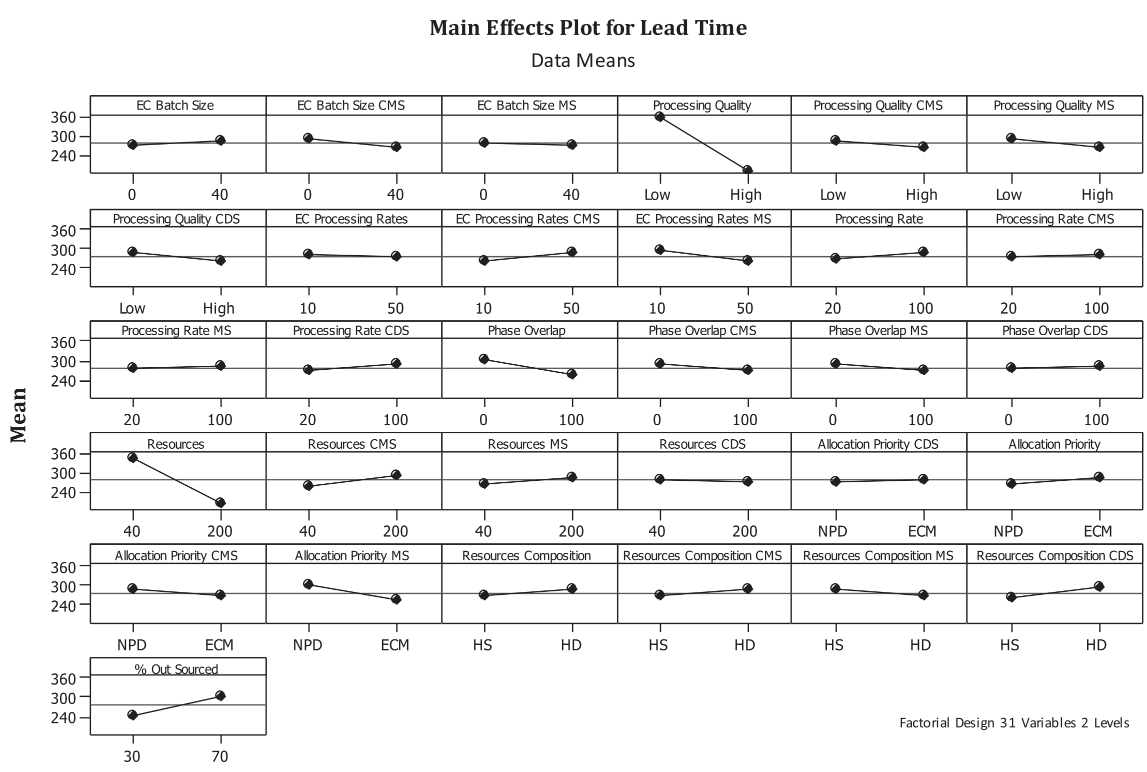

Figure 3. Effect of the process parameters on lead time using factorial design approach of DOE.

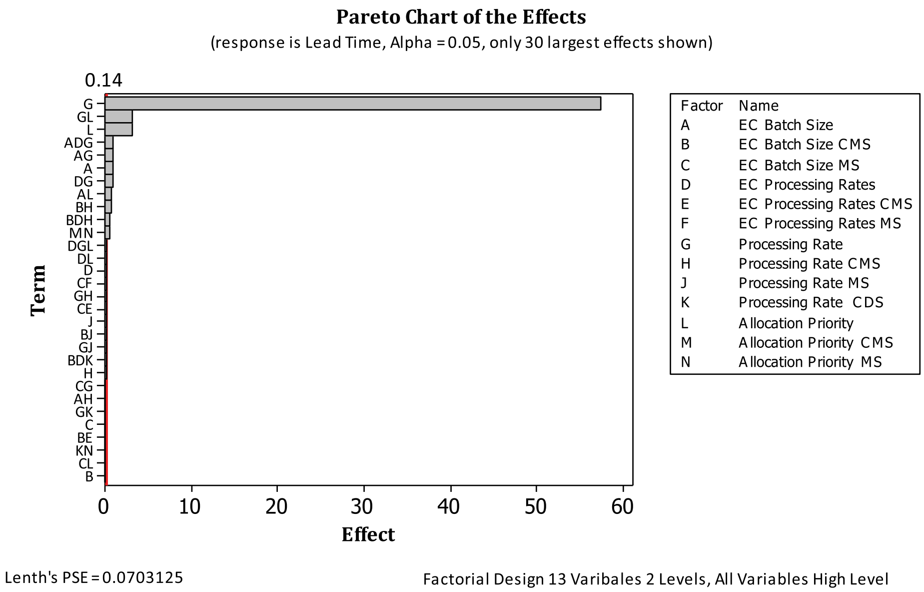

Figure 4. Pareto chart showing the effects of selected 13 factors on lead time with all variables at high state.

The increase in the quantity of factors and magnitude of the effect, from the case when variables are kept constant at level high to level low can be observed in Figures 3 and 4. When the variables are set high (Figure 4), the OEM has a significant effect on the NPD lead time. The variables, processing rate, allocation priority, EC batch size and combinations of these variables demonstrate the highest impact on the lead time, followed by combinations of concept to manufacturing supplier and manufacturing supplier variables. When the variables are set low (Figure 5), the OEM affects the lead time significantly followed by the suppliers. The effect of suppliers has considerably increased compared to the previous case. It can be observed that, the influence of the suppliers on the NPD lead time is greater when the process variables level is low compared to high.

Case 3: The model has been simulated by varying a single variable, while all the rest of the variables are kept constant at two levels, low and high. Each parameter is simulated for a range of five values to study the effect of each of them on the NPD lead time, when all the other variables are at low and high levels. From the simulated results, the effect of each parameter of the OEM and suppliers on the NPD lead time is studied and discussed below. Graphs are drawn to

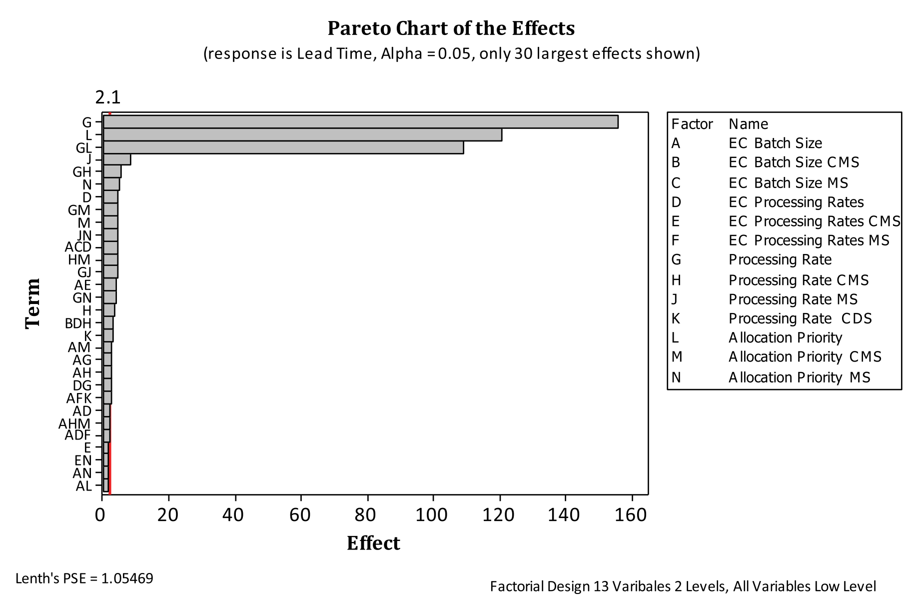

Figure 5. Pareto chart showing the effects of selected 13 factors on lead time with all variables at low state.

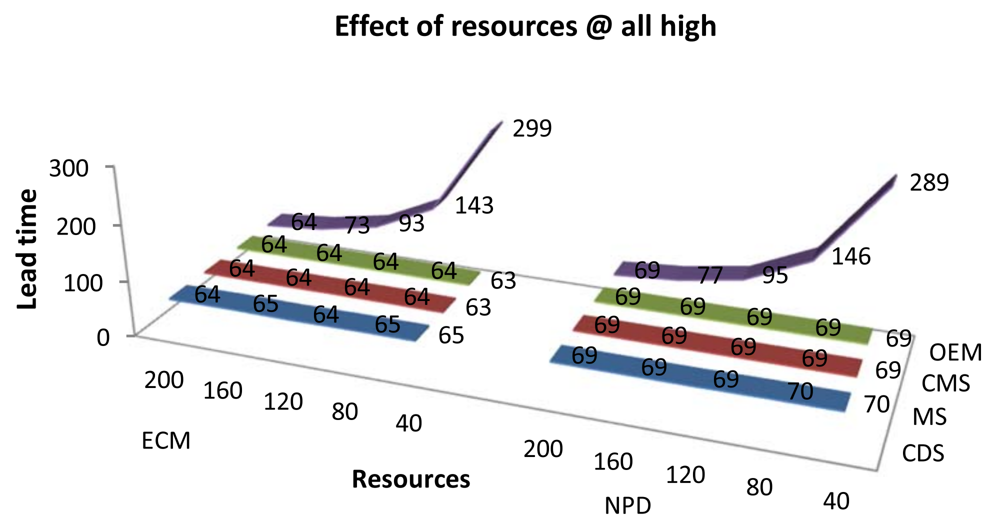

Figure 6. Effect of organisation resources when all variable are set constant at high.

compare the effect of similar parameters of the organisations that are part of the supply chain and the resource allocation priority strategy of the supply chain on the OEM lead time.

Effect of resources

The resources of the OEM differs from the trend (of decreasing or increasing lead times) at some point in the graph, indicating the presence of a specific number of resources that would result in lowest lead time (Figures 6 and 7) under the simulated conditions. The resources of the OEM vary with the change of the status of all the other variables from high to low, while the number of resources of the suppliers does not seem to affect the lead time, given that the quantity is more than the minimum 40. For the case when the variables are set at high (Figure 6), 200 resources for the OEM seem to result in lowest NPD lead time. The slope is relatively high at lowest point of the curve (Figure 6) indicating that there can be further decrease in lead time with increase in OEM resources.

The resources of the organisations do not have any significant effect when the variables are set at low (Figure 7) compared with cases when the variables are set at high, where the OEM resources have a significant effect on the lead time. It can also be noted that 80 resources is optimum for the OEM, MS and CDS while 40 resources is optimum for CMS.

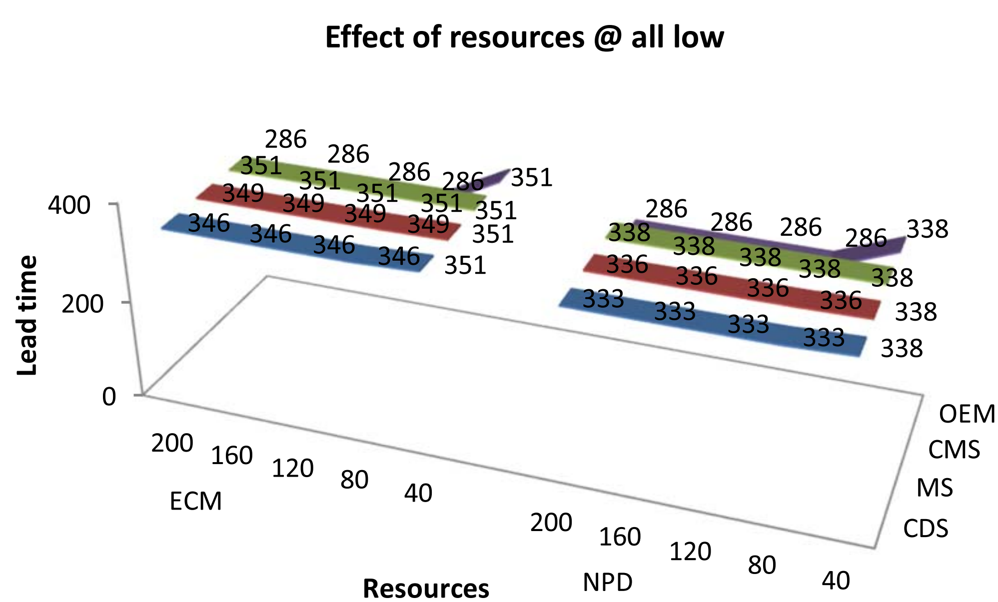

Figure 7. Effect of organisation resources when all variable are set constant at low.

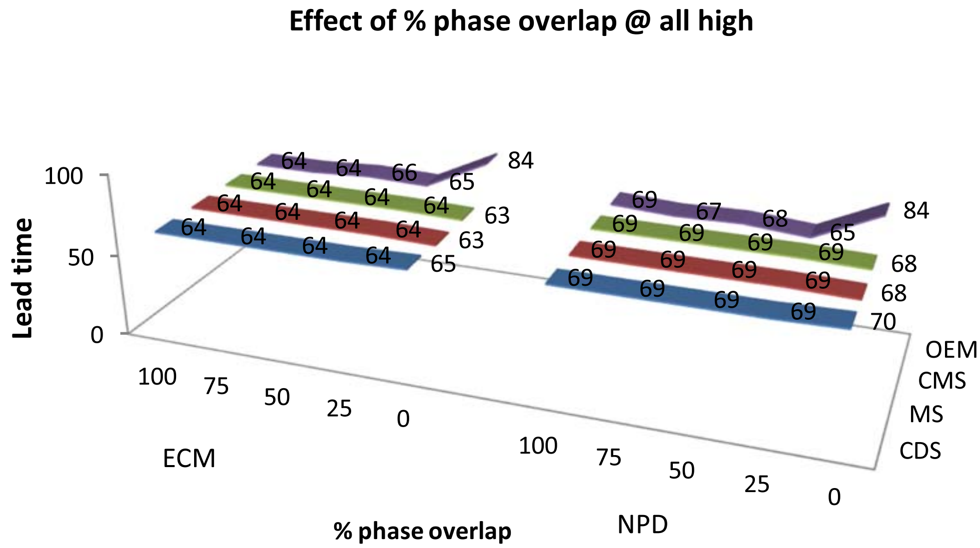

Figure 8. Effect of percentage phase overlap when all variable are set constant at high.

Effect of percentage phase overlap

The percentage of phase overlap of the suppliers does not affect the lead time significantly when the variables are set at high (Figure 8), but when the variables are set at low (Figure 9) the phase overlap of the manufacturing supplier effects the lead time. Zero percent phase overlap for the suppliers is advantageous when the variables are set at high but when the variables are set at low a non-zero phase overlap is advantageous. In all the cases 0% phase overlap deteriorates the OEM performance thus increasing the lead time. Only the OEM phase overlap seems to have a strong influence on the lead time and it is greater when the variables are set at high compared with low. When the variables are set at high the ECM resources allocation priority is advantageous, but when the variables are set at low the NPD resources allocation priority is advantageous.

Effect of processing quality

The processing quality of the suppliers does not affect the lead time significantly compared with the OEM processing quality, which has a strong effect on the lead time. The higher the processing quality of the OEM, lower is the NPD lead time. When the variables are set at high (Figure 10) the ECM resources allocation priority is advantageous for all levels of processing quality of the organisation in the supply chain, but when the variables are set at low (Figure 11)

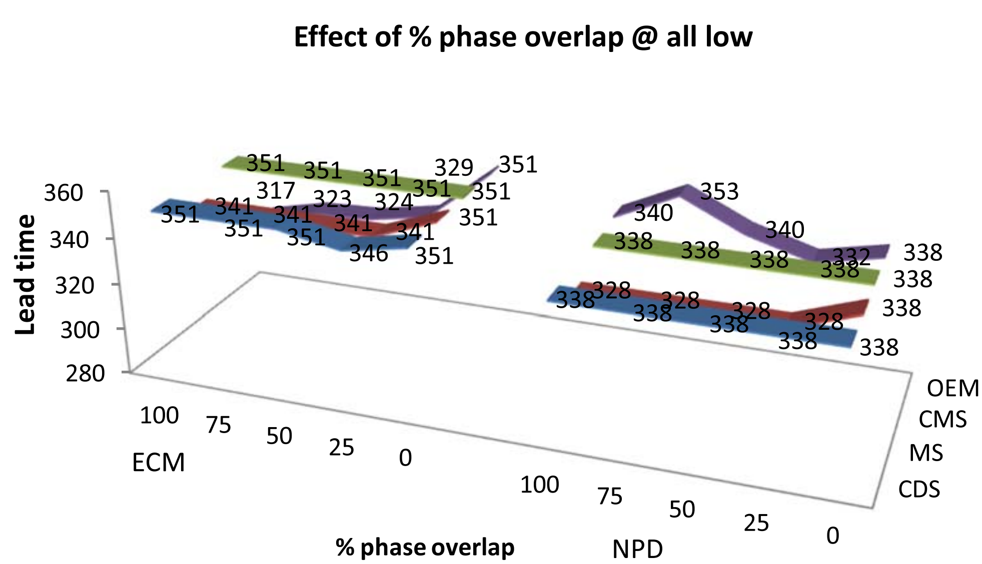

Figure 9. Effect of percentage phase overlap when all variable are set constant at low.

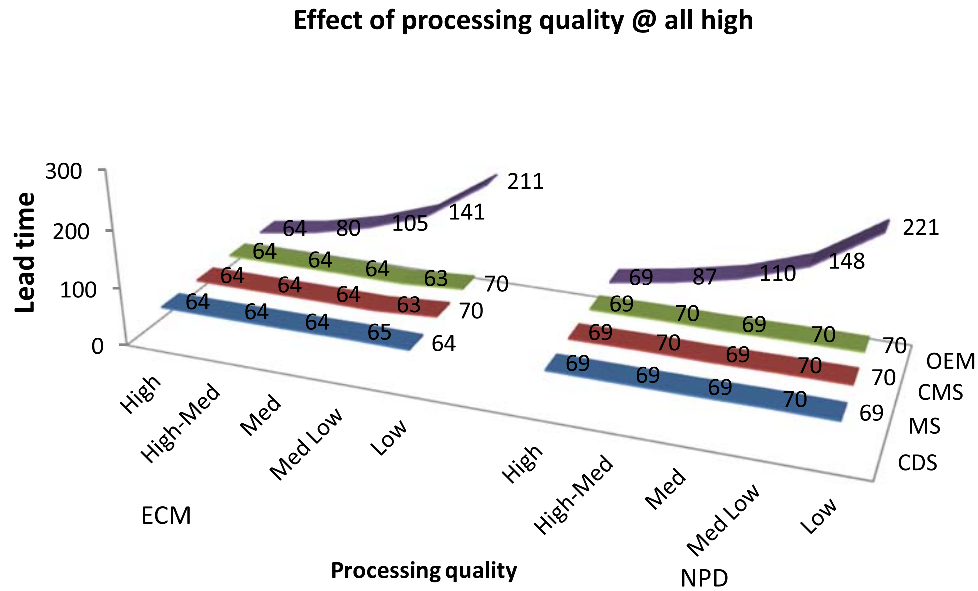

Figure 10. Effect of processing quality on lead time when all variable are set constant at high.

the NPD is advantageous. The actual values of the processing quality for each of the NPD phases can be seen in Table 2. Assuming that the OEM designs the product components that integrate components supplied from suppliers; the possibility of EC propagating and resulting in more changes further down the product hierarchy is more for ECs resulting from OEM compared with the suppliers. This justifies the observation that, high processing quality of the OEM would result in lower number of ECs and thus lower NPD lead time.

Effect of NPD processing rate

The NPD processing rates of the suppliers do not have significant effect on the lead time assuming that it is more than the minimum (20 resources) considered. The NPD processing rate of the OEM has a considerable influence and also indicates an optimum processing rate, corresponding to the status of the other variables (high or low). When the variables are set at high (Figure 12) the optimum processing rate for NPD allocation priority is 60, and for ECM priority it is 80 components per week. Similarly with variables set at low (Figure 13), the optimum NPD processing rate of OEM is 20 for both NPD and ECM allocation priorities. It can be observed that the optimum NPD processing rate, resulting

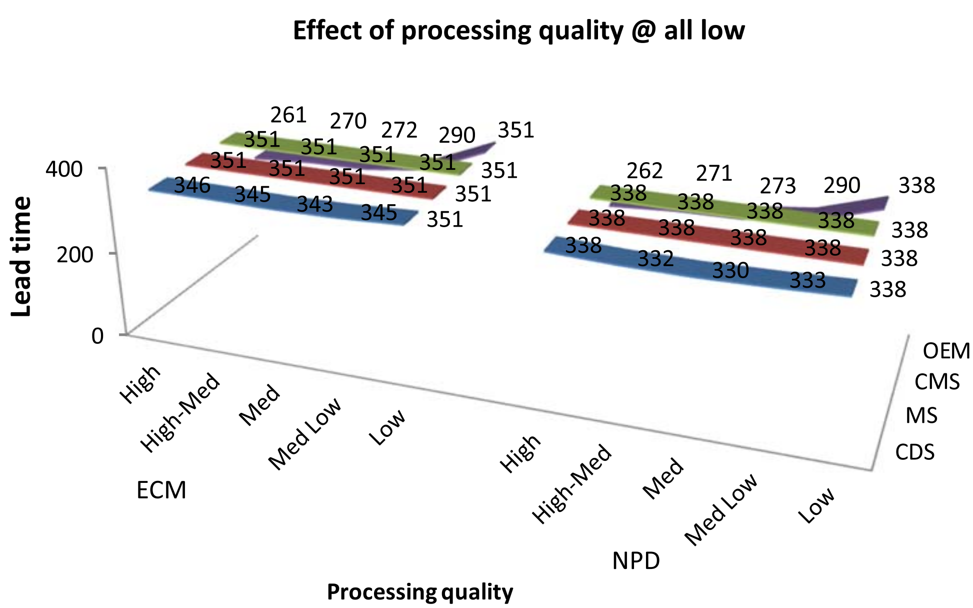

Figure 11. Effect of processing quality on lead time when all variable are set constant at low.

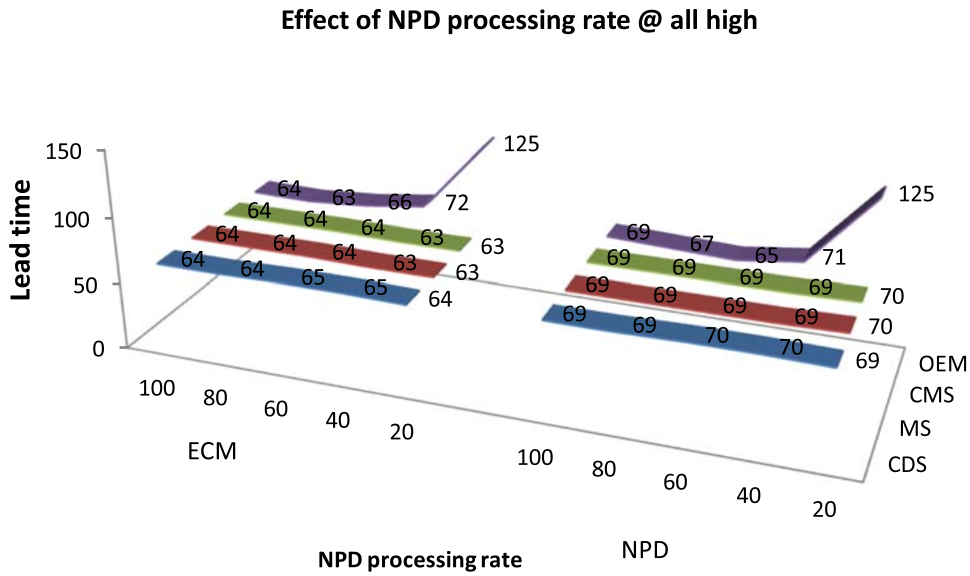

Figure 12. Effect of NPD processing rate on lead time when all variable are set constant at high.

in lowest lead time keeps shifting according to the state of the variables. It can also be observed that ECM priority is advantageous when all the other variables are set at high (Figure 12) while NPD priority is advantageous when the variables are set at low (Figure 13).

Effect of ECM processing rate

The ECM processing rates of the suppliers do not affect the lead time (Figures 14 and 15) significantly implying that the lowest processing rate of 10 components per week is good enough for both the cases (variables levels high, and low). ECM processing rate has greater effect on the lead time with ECM resource allocation priority, compared with NPD allocation priority. The ECM processing rate for the OEM has an optimum value, which results in the lowest NPD lead time, when the variables are set at high (Figure 14). The optimum value of OEM processing rate is 20 components per week, when the variables are set at high for both NPD and ECM allocation priorities. When the variables are set at low (Figure 15), then an ECM processing rate of 10 components per week for whole supply chain is good enough to avoid deteriorated process performance.

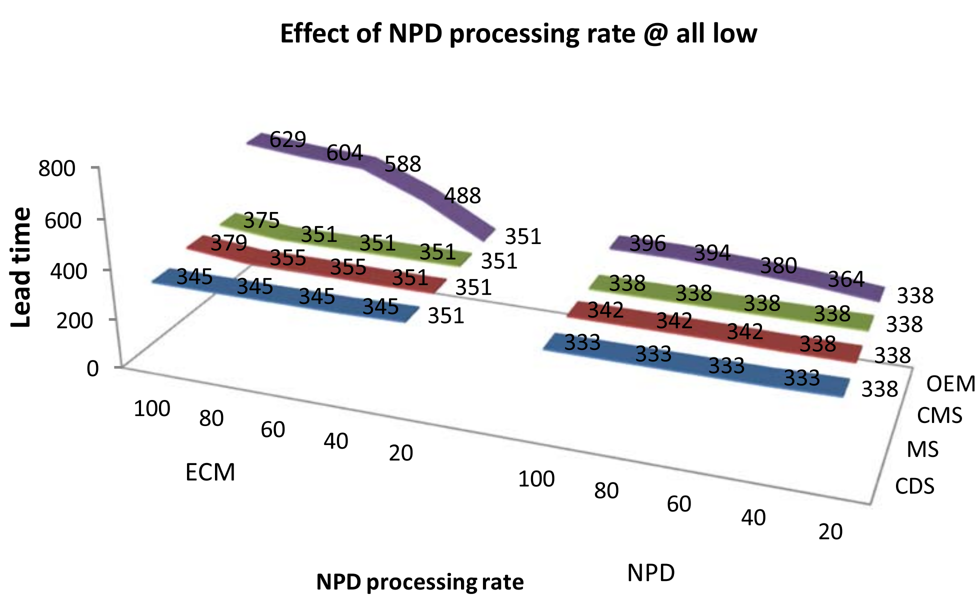

Figure 13. Effect of NPD processing rate on lead time when all variable are set constant at low.

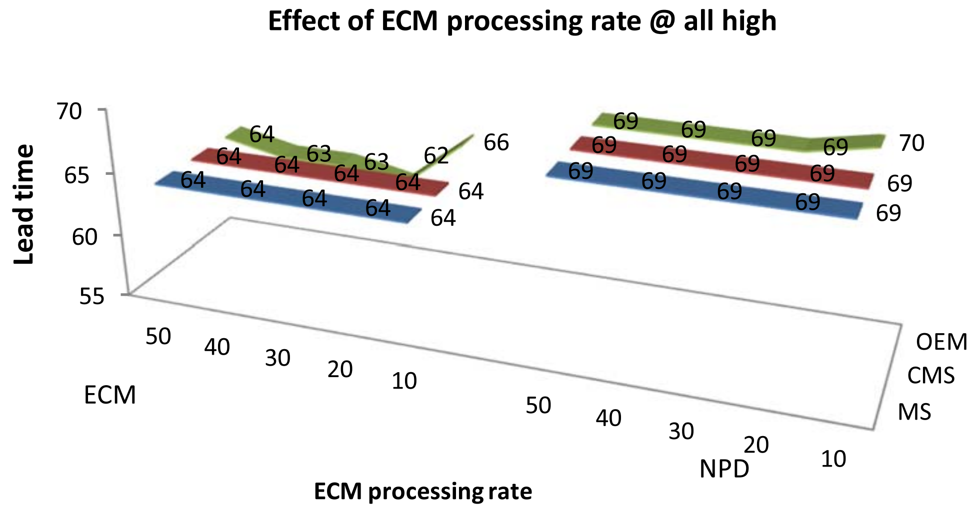

Figure 14. Effect of ECM processing rate on lead time when all variable are set constant at high.

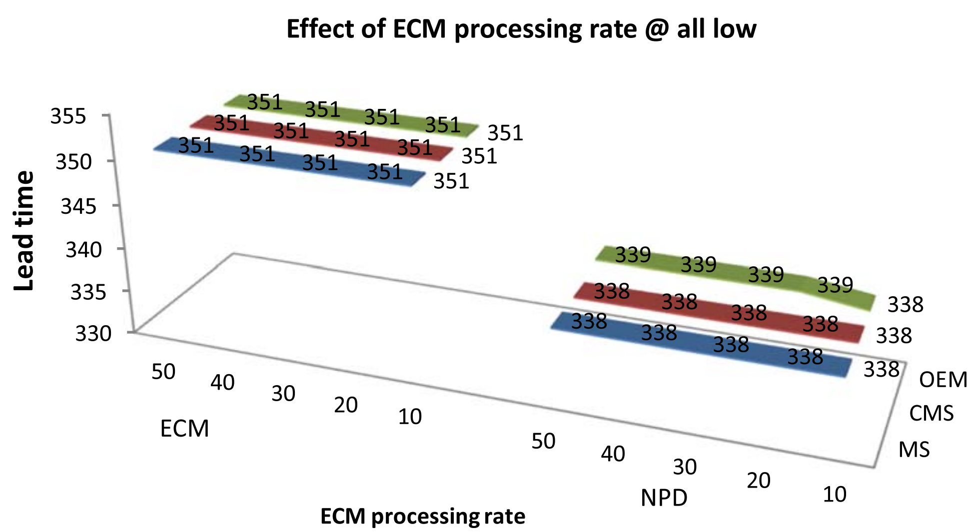

Figure 15. Effect of ECM processing rate on lead time when all variable are set constant at low.

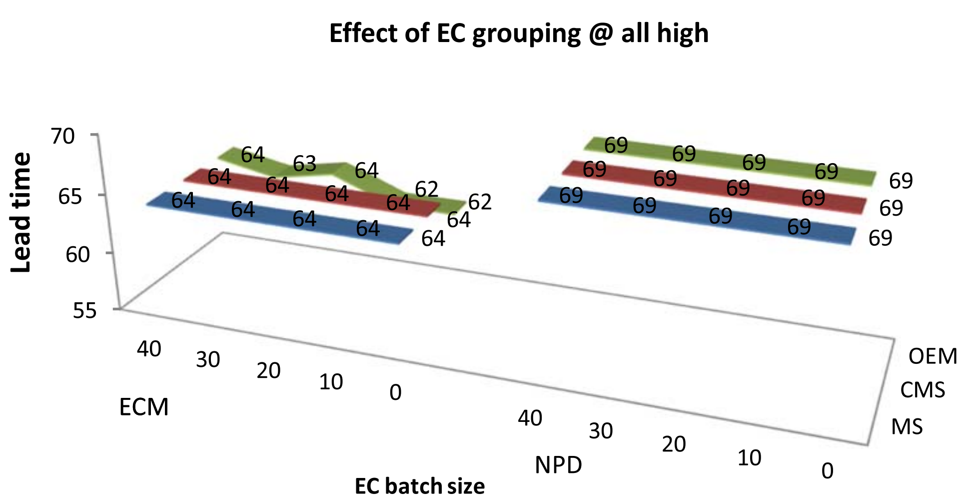

Figure 16. Effect of EC grouping on lead time when all variable are set constant at high.

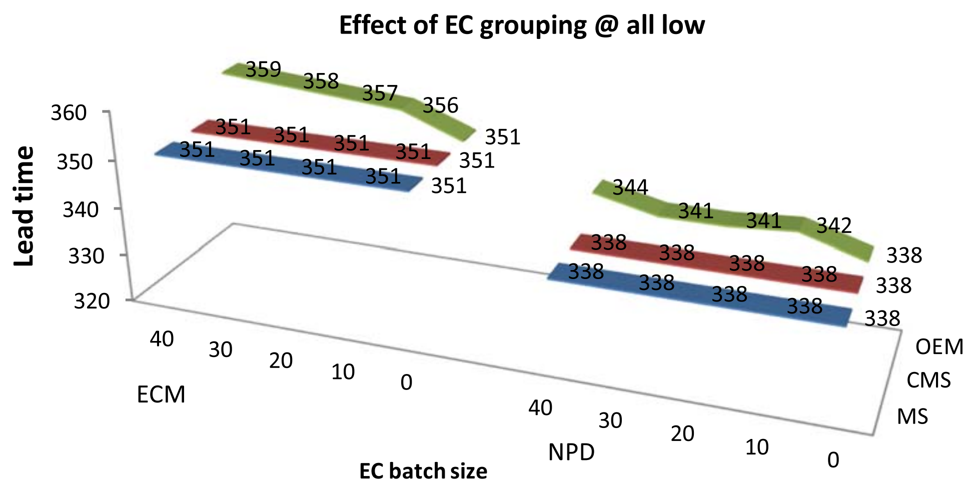

Figure 17. Effect of EC grouping on lead time when all variable are set constant at low.

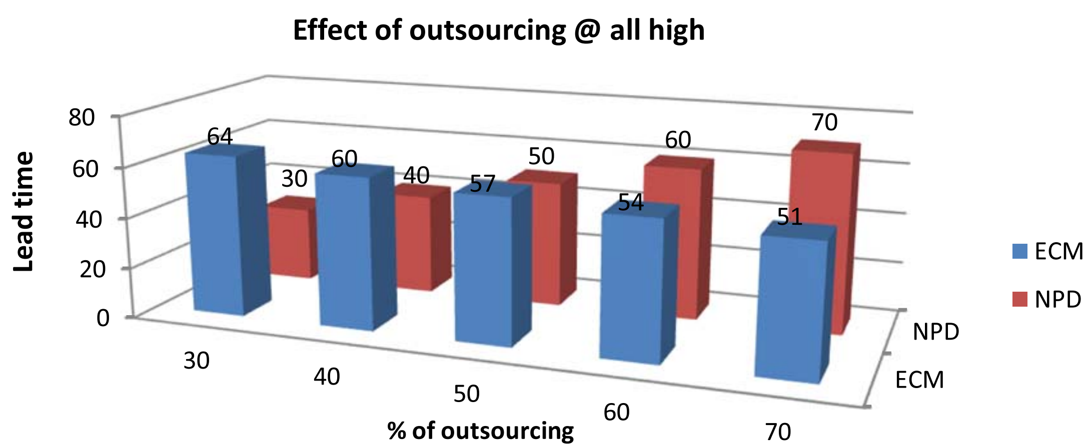

Figure 18. Effect of outsourcing on lead time when all variable are set constant at high.

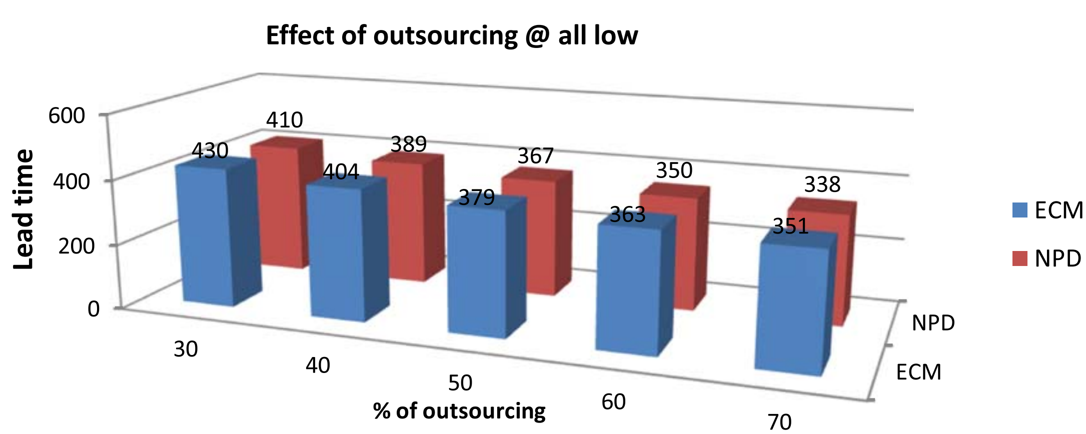

Figure 19. Effect of outsourcing on lead time when all variable are set constant at low.

Effect of EC grouping

The EC grouping of the OEM has considerable effect on the lead time in most of the cases (Figures 16 and 17). The suppliers do not have any significant effect on the lead time for all the variable levels and allocation priorities. A group size greater than 0, either degrades or does not improve the OEM performance, indicating that grouping of ECs is not advantageous. But EC grouping can be considered as long as it does not deteriorate the process performance because processing in groups is considered to be more productive (Reddi and Moon 2011a) compared with individual components.

Effect of outsourcing

When the variables are set at high the lead time for NPD resource allocation priority increases with increase in outsourcing, but with ECM resource allocation priority it decreases with increase in outsourcing. This indicates that the outsourcing is advantageous with NPD resource allocation priority, while it is the opposite with ECM allocation priority, with the variables set at high (Figure 18). This indicates that when an organisation has adequate resources and good NPD and ECM processes in place to ensure high processing quality, it would be advantageous to follow the NPD or ECM resources allocation strategy depending upon the extent of outsourcing. For higher percentages of outsourcing, ECM priority is advantageous and for lower percentages of outsourcing NPD priority is advantageous.

When the variables are set constant at low (Figure 19) then it is always advantageous to follow the NPD priority resource allocation strategy.

6. Conclusions and future work

The conclusions from the simulation results can be summarised as following,

- Based on these results we can ratify that, all the system parameters should be complementing each other in order to attain the best achievable NPD lead time. The best or lowest NPD lead time is not possible by managing a few process parameters.
- When a few parameters are assumed to be constant there exists a value for other parameters beyond which there is either no improvement in the performance or degraded performance. For example, when all process parameters are constant there exists, a processing rate beyond which there is no decrease or change in lead time.
- The effect of any single process parameter on the NPD lead time varies with respect to the status or magnitude of the other system parameters.
- The OEM process parameters always affect the NPD performance while the effect of the suppliers is dominant only when the process parameters are low or limited.
- NPD resource allocation priority results in lower NPD lead time with scarce resources and low quality process conditions; while ECM resource allocation priority results in low lead time with adequate resources and high and moderate quality process conditions.
- Grouping ECs does not make any difference to the process performance and hence processing the ECs, as they are proposed is advantageous.

The accuracy of the model results depend on the numerical values of the parameters. Though the numerical values are not used from an industry, realistic values (Ahmed and Kanike 2007; Langer et al. 2012; Reddi 2011; Reddi and Moon 2012) were assumed to study the effect of the NPD and ECM process parameters on the supply chain performance. Future work can include expanding the number of suppliers and using industry data to access the practical use of these kinds of models. The examined process variables have been studied with only two levels to limit the number of simulation runs, In the future three or more levels of selected process variables can be examined to study the interactions. The templates proposed by Reddi and Moon (2011a) can be used to model a supply chain efficiently and economically with minimal efforts and expertise. Use of system dynamics makes it easier to be understood (Forrester 1968; Sterman 2000) by personnel with minimum or no simulation knowledge. From the results it can be stated that this model would be helpful to the managers in managing and planning the NPD and ECM processes.

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