The Use of a GERT Based Method to Model Concurrent Product Development Processes

Richard Graham Nelson [a], Amir Azaron [a,b,1], Samin Aref [c]

[a] Michael Smurfit Graduate School of Business, University College Dublin, Carysfort Avenue, Blackrock, Co. Dublin, Ireland
[b] Department of Industrial Engineering, Istanbul Sehir University, Istanbul, Turkey
[c] Department of Computer Science and Te Pūnaha Matatini, University of Auckland, Auckland, Private Bag 92019, New Zealand

Nelson, Azaron, Aref, The use of a GERT based method to model concurrent product development processes, European Journal of Operational Research, Volume 250, Issue 2, 16 April 2016, Pages 566-578, ISSN 0377-2217, http://dx.doi.org/10.1016/j.ejor.2015.09.040.

Received	19 November 2014
Accepted	21 September 2015
Available online	9 October 2015
Published	16 April 2016

Abstract

This paper proposes a time-computing model using the Graphical Evaluation and Review Technique (GERT) to analyse concurrent New Product Development (NPD) processes. The research presented here differs from previous work carried out on concurrent engineering. First, we conceptualise a concurrent NPD process using the GERT scheduling technique and derive a method of modelling the information and communication complexities within the process. Secondly, we extend previous research carried out on concurrent engineering and incorporate it within our model. Finally, we present an alternative method of analysing concurrent NPD process for both researchers and project managers alike. The GERT model developed in this paper was successfully employed at two NPD firms located in Ireland and Iran.

Keywords: Project management; New Product Development (NPD) process; Graphical Evaluation and Review Technique (GERT)

1. Introduction

New Product Development (NPD) is concerned with the process of getting any new product or service to market. In NPD, speed-to-market is viewed as a vital weapon which can yield competitive advantage, realise higher profits and market share, and exploit

1 Corresponding author. E-mail: amirazaron@sehir.edu.tr.

opportunities within the market place (Cooper 2001). In recent years, companies have adopted acceleration techniques to scheduling NPD projects, focusing more on concurrent engineering.

The conventional approach to scheduling projects focuses on the traditional sequential approach, where subsequent stages of a project commence only when the preceding stages have terminated and have supplied complete and final information. This sequential approach to project management requires a great deal of time and as such, has become a barrier to entry for projects in fast-moving markets. Over the past three decades, concurrent engineering has become a guiding stratagem for reducing the time-to-market for new products. In contrast to the sequential approach, activities in concurrent engineering are jointly managed to work in parallel; allowing following stages in a project to begin prior to the completion of earlier stages. In effect, the concurrent engineering strategy significantly reduces the project development time, facilitating an increased speed-to-market. Furthermore, by enabling different operations to be undertaken concurrently, the needs of the project as a whole are better satisfied (Jones 1997). This allows engineers and designers to coordinate their work and make mutual adjustments in their designs which might be necessary to avoid compromises at later stages. While there is substantial research showing that concurrent engineering practices can dramatically reduce project lead times, the successful application and modelling of concurrent NPD processes has proven difficult due to the increased level of network complexity.

In concurrent NPD processes, the interdependencies within the project are bi-directional and constrained by physical, resource and knowledge based relationships. These constraints are recognised by Ford and Sternman (2003) as precedence relationships, activity durations, information dependencies, the availability of work, coordination mechanism, and the number, skill and experience of project staff. Depending on the degree of network overlapping, concurrent engineering relies on a complex myriad of information flows and bi-directional interdependencies. The overlapping of dependent phases means that many events are initiated on designs or specifications that are incomplete or may change over time. Therefore, concurrent engineering practices generally incorporate a high probability and need for activity iterations and rework loops on errors or omissions that may arise during the process. Oftentimes, this leads to increased development costs (Krishnan 1996; Roemer, Ahmadi, and Wang 2000; Terwiesch and Loch 1999). Furthermore, NPD processes create additional planning complexities as the data required for modelling are only partially known initially (Smith and Morrow 1999) and much of the input data is generated on speculation.

The majority of difficulties surrounding the representation of concurrent NPD networks concern: communication complexities in the transfer and flow of information, activity rework, overlapping strategies, resource usage, and the implementation of a new strategy. Since concurrent NPD project networks are based on complex physical and information dependencies, current methods of modelling concurrent NPD processes rely heavily on the capacity of the modeller to represent the NPD process using conventional scheduling techniques.

The Project Evaluation and Review Technique (PERT) has long been established in industry as a tool for planning and managing projects. While recent advances use Markov PERT networks to model queuing, resource allocation, and multi-objective analysis (Azaron, Katagiri, and Sakawa 2007; Azaron et al. 2006), the shortfalls are in its rigid analysis of the project structure and inability to represent complex interactions (Wang and Lin 2008). Despite this, PERT-path developed by Pontrandolfo (2000) is particularly interesting as it draws strong parallels with other scheduling techniques while addressing the optimistic bias of PERT.

The majority of current modelling carried out on concurrent engineering (Carrascosa, Eppinger, and Whitney 1998; Browning and Eppinger 2002; Yan et al. 2010) focuses on the use of the Design Structure Matrix (DSM). While the DSM is a widely used scheduling tool, it has several drawbacks: activity iteration implies the repetition of the same previously completed activity (Lévárdy and Browning 2009); and it does not provide a graphical output or flow-diagram of the information dependencies and communication flows necessary for implementation.

The Graphical Evaluation and Review Technique (GERT) technique developed by Drezner and Pritsker (1965) and Pritsker and associates (Pritsker 1966; Pritsker and Happ 1966; Pritsker and Whitehouse 1966) provides an alternative platform to resolve the modelling complexities associated with concurrent NPD processes. The precedence of probabilistic branching and network loops allows for the inclusion of both network feedback and activity rework to be considered within a stochastic network. The model has a predictive power within its domain and the knowledge acquired from its analysis can be used in making critical decisions involving the selection and evaluation of a network strategy. Furthermore, the output of GERT provides managers with a holistic graphical representation of the concurrent process necessary implementation.

Up until now, few studies have focused on the use of GERT to model NPD processes. Bellas and Samli (1973) was the first of its kind to investigate the use of GERT in sequential

NPD processes and market research. Bellas and Samli used GERT to carry out a sensitivity analysis on project controls. Moore and Clayton (1976) applied GERT as a holistic scheduling method to a sequential NPD process. Taylor III and Moore (1980) explored the use of Q-GERT, as an alternative to the PERT-CPM approach, on stages of research and development in sequential NPD projects. Aytulum and Guneri (2007) applied GERT to a sequential product development process in an attempt to evaluate the adaptability of the model to a business process. Wu et al. (2010) analysed various risks in concurrent product development projects through a tree-dimensional early warning approach, incorporating GERT. Finally, Peña-Mora and Li (2001) developed a hybrid axiomatic design incorporating GERT and systems dynamics model to analyse fast-track construction projects.

Product development projects are perhaps the best examples of GERT applications however, its application to concurrent processes and in particular to NPD concurrent processes has yet to be fully examined. This paper employs GERT as a time-computing scheduling technique to model concurrent NPD processes. The proposed network resolves a lot of the drawbacks associated with conventional scheduling tools, providing an alternative method that explicitly represents and models the complexities arising from concurrent NPD processes. The results of this paper will provide managers and researchers with a method of modelling and analysing concurrent strategies with superior performance in NPD processes. Through this research, we propose a GERT based time-computing model concerning the project completion time by acquiring and modelling the dynamic characteristics of network activities and information flows in a concurrent NPD process.

The layout of this paper is as follows: Section 2 discusses the theoretical background motivating our approach, after which Section 3 introduces the proposed GERT model. Section 4 forms the basis of a research case study, and Section 5 outlines conclusions drawn and areas for future research.

2. Methodology

This section discusses the main methodological issues of the research including GERT network features, research limitations, and results verification and validation methods.

2.1. GERT Network Features

The GERT network represents the lowest possible level of defined activities within a project. This involves the decomposition of work packages into scheduled activities to provide a basis for estimating, executing and controlling the project. In GERT, a directed branch or arrow with transmission parameters of time and probability is used to represent a scheduled activity or communication path between two nodes.

The characteristics of GERT networks include:

- Probabilistic Branching: GERT networks may contain probabilistic branching, deterministic branching, or a combination of the two. This allows for the representation of communication transfer links between both coupled and non-coupled activities.
- Network Looping: GERT networks allow looping to be included. In NPD, it implies redoing or revising previously completed activities and that certain events may be realised more than once. Smith and Eppinger (1997) stated that understanding activity interaction and process iteration is fundamental to accelerating product development processes.
- Node Realisation Logic: The realisation of a node in GERT can be specified to occur with one or more completions of activities present in that node. This feature of GERT consists of two notations: the AND node and the OR node. As shown in Figure 1, the AND node will be released only if all the branches leading to the node are realised. Similarly, the OR node consists of two notations: F denotes the number of predecessor activities that must first be completed for the first realisation of the node; and S denotes the number required for subsequent realisations. The OR node will be realised the first time once F of the total number of activities leading to the node are realised. If the node is contained in a loop, then the node can be realised subsequent times once S of the total number of activities leading to the node are realised.
- Distribution of Activity Times: GERT networks facilitate a selection of activity time distributions (normal, beta, gamma, etc.). In practice it is far more common to find multiple time distribution types for specific activities.
- Terminal Event (Sink Node): GERT networks allow for sink nodes to be incorporated into the network. In reality projects may often ceased or be withdrawn at a number of stages within a project depending on the scope and resources available.

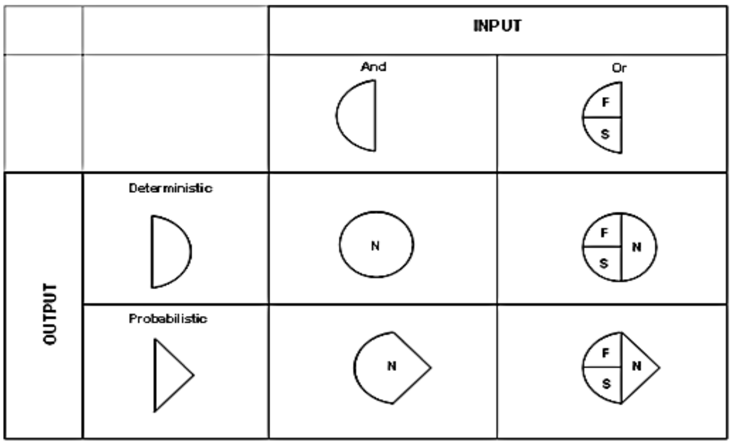


Figure 1. *GERT Symbolic Functions*

2.2. Limitations of the Method

One of the major limitations associated with concurrent engineering is the fact that the activity iterations cannot be precisely estimated. It can be argued that the majority of feedback iterations maintain experience from initial project work and as a result, acquire a shorter lead time on previously completed work. The durations associated with feedback loops within our proposed GERT model assumed that the iteration is equal in duration to the initial project work. While this may be the case in certain circumstances, in practice, this would rarely be the case and leads to overly biased pessimistic project lead times.

Moreover, this study does not consider either the effects of concurrent engineering on product quality or the scarcity of resources. Resolving each of these limitations will lead to a potential further research addressed to in the last section of this study.

2.3. Verification and Validation of the Results

There are different types of verification and validation methods deployed in this study for different phases of the research. The first is a preliminary analysis of the data for sufficiency that is performed after data gathering and before the modelling. The second validation method includes a Goodness-of-Fit test after simulating the sequential NPD process. This test is simply determining whether the distribution functions estimated are fit to the real observations. The third is genuinely a verification method to compare the simulation results and attributes with the real case. After successfully passing the aforementioned three, the hypothetical concurrent NPD process is simulated and Antithetic Variables method is performed. Then, the final method evaluates the validity of simulation results in terms of consistency between runs by performing another Goodness-of-Fit test and a Kolmogorov-Smirnov test.

3. GERT Simulation

Since complex systems are often too complicated to be solved analytically, the majority of GERT networks are modelled using either Monte Carlo simulation or Markov Chain Monte Carlo (MCMC), whereby operating characteristics of the system can be observed. Yi-song and Feng (2009) outlines the process in developing a simulation and the following steps have become an accepted method of applying Monte Carlo simulation to a GERT system:

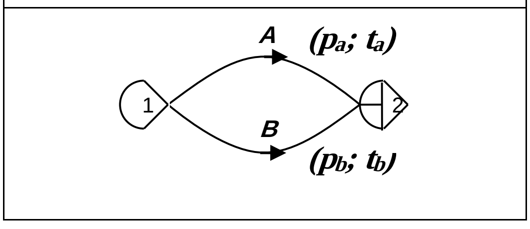
Activity Definition

The activity definition process will identify the deliverables at their lowest possible level or work packages. Project work packages are then decomposed into smaller components called scheduled activities to provide a basis for estimating, scheduling, executing, and monitoring and controlling the project. A scheduled activity is generally regarded as any portion of a project that consumes time or resources and has a definable beginning and ending (PMI 2008).

Network Characterization

Communication flows and information transfers are the most important features within an NPD process. Communication in product development is regarded as the number of information transfer links between project teams (Brooks 1975). In GERT Simulation, each communication path and network activity is randomly determined by the probability of the event occurring. Accordingly, a random value may be associated with probabilistic branches. That is to say, deterministic branches have an associated probability equal to one. In order for a probabilistic branch to be realised, the random value must lie within the branch's probability limits. For example, in a network containing two activities, *A* and *B*, with associated probabilities, *p(a)* and *p(b)*, and a random value, *R*

Topological Representation



where: $p(a) + p(b) = 1$

Activity A is realised if: $0 \le R \le p_a$; and activity B is realised if: $p_a \le R \le 1$.

In turn, each activity duration is generated from a random time specific to the time distribution density function of that activity. Where the cumulative probability function, *F(t)*, for the activity time corresponds directly to a random value *R* as given by (1):

$$F(t) = R = \int p(t).\,\mathrm{d}t \qquad 0 < t < \infty \tag{1}$$

where:

R: random number, such that $0 \leq R \leq 1$;

$p(t)$: probability density function for the activity time, t.

Activity Rework

At the heart of concurrent engineering lies the rework principle. As activities are initiated on the basis of speculative information, extended activity rework is required to amend any errors. It directly impacts the project resources and causes an increase in development costs. In order to model concurrent NPD process using GERT, we must first define the rework principle.

The issue of activity rework in concurrent engineering was first addressed by Krishnan (1996) and Krishnan, Eppinger, and Whitney (1995; 1997) where the authors adopted an information-processing or fast evolution view of product development. The authors introduced the concept of upstream information sensitivity (*evolution*) and downstream iteration (*sensitivity*) in the exchange of product information. Several authors (Carrascosa, Eppinger, and Whitney 1998; Roemer, Ahmadi, and Wang 2000; Roemer and Ahmadi 2004) used adaptations of models developed by Krishnan, Eppinger, and Whitney to characterize the rework priori. Yan et al. (2010) extended this concept and found that the shorter the overlap between activities, the lower the probability of wrong predictions being made to downstream activities caused by incomplete information. Yan et al. (2010) presented the rework probability distribution, $p_{ij}(t)$, of an upstream activity *j* providing incomplete information to a downstream activity *i* at design stage *t*, as a function of the degree of overlap between the two activities as given by (2).

$$p_{ij}(t) = \frac{a_{ij}aT_i}{T_j}(1 - \frac{t}{T_j - r_j})^b \tag{2}$$

where:

a_{ij}: degree of information dependence between activity *i* and *j*, $0 \leq a_{ij} \leq 1$;

T_i : normal activity duration;

T_j: overlapping duration if rework is omitted;

t : fast evolution duration;

r_j: total rework time for upstream activity *j*;

a: a coefficient of complexity of the activity, for $0 < a < 1$;

b: a coefficient of experience of the employees, for $0 < b$.

Yan et al. (2010) extended the rework probability function and proposed an extended rework duration. Whereby, if there exists overlapping between two activities, i and *j*, where the start time of activity i is later than that of activity *j*, then the extended rework time of i due to this overlapping can be expressed as an integral stated in (3).

$$r_{ij} = \int_{x_i - x_j}^{T_j + r_j} p_{ij}(t).\,\mathrm{d}t \qquad (3)$$

where:

x_i: start time of activity *i*;

x_j: start time of activity *j*.

Activity rework and communication complexities resulted from concurrency can be modelled in GERT by extending Yan et al.'s probability priori through probabilistic branching and network loops. The variables of which are established through both primary and secondary information sources.

Consider the simplified concurrent NPD process shown in Figure 2, with the degree of activity overlapping proportional to a lag time, t_j. The probability and duration of rework occurring (p_{ij} and r_{ij}, respectively) is modelled as a separate activity. Based on this model, overlapped activities have a corresponding extended rework. The feedback loops arising resulted from errors or omissions within the network are initiated from probabilistic nodes and are shared with the activity rework.

The branches from nodes 2-4, 5-7, 8-10, and 11-13 represent dummy activities with zero time and returns the completed activity back into the network. The inclusion of the dummy activity in our model ensures that the upstream task always finishes before the downstream task is complete. This is consistent with the majority of NPD processes, however can be adapted accordingly.

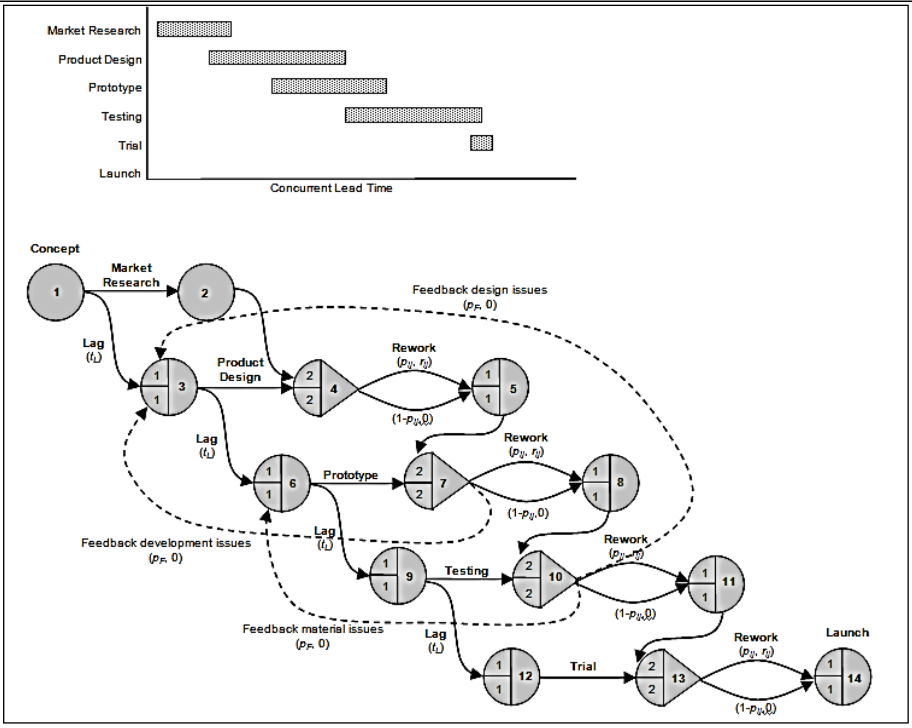


Figure 2. *GERT Concurrent NPD Process*

System Analysis

Once random numbers are generated and the network paths are identified in accordance with their branch probabilities, the cumulative stochastic times of each activity are aggregated for each path according to their time density distribution functions. Each path through the network is cumulated with the total project lead time established. The number of simulations, *N*, carried out on the network is then identified.

The question regarding the number of simulation samples depends largely on the type and size of the GERT model. Bellas and Samli (1973) found that a sample size of 400 replications is more than adequate. However, several authors (Moder, Phillips, and Davis 1983) and also an empirical study by Crandall (1976) indicate that a sample size of 1,000 replications maintains an adequate level of confidence and accuracy. Due to the nature of Monte Carlo and the number of replications, users should be wary of pseudo-random numbers and only true random numbers should be considered.

Once the GERT simulation is validated conditions may be placed on the system, for instance resource allocation and cost may be considered within the network. The system analyst may consider a sensitivity analysis of the process by applying a percentage change in the duration of a particular activity and identifying the controlling points of schedule duration or cost. Finally, simulation may be used to compare two or more entirely different systems. For example, management may wish to model two dissimilar process strategies prior to the modernisation of an existing system. If alternative networks were being considered, simulation can be used to provide estimates of system performance according to various operating characteristics.

4. Case Study

4.1. Case Study Research Design

As project scheduling is a discipline in which practical knowledge is as valuable as theoretical knowledge, the theoretical ideas of this study are tested on two different cases from diverse industries where NPD is the practice in common. It is a widely accepted argument that case studies contribute to scientific development while the reliability of the findings obtained is in direct correlation with the comprehensiveness and diversity of cases when verified objectively (Flyvbjerg 2006).

This section focuses on detailed practical examples of the theoretical methodology discussed earlier to build an evidence-informed planning approach for NPD processes.

There are three different types of case studies including explanatory, exploratory, and descriptive case studies all defined by Yin (2003) in one of the most cited case study research design references. This case study belongs to the first type as it tries to explain the presumed causal links in practice in order to reveal a more beneficial method that is too complicated to be experimented without running a simulation. Although, multiple case studies are time-consuming and expensive, they bring about robust and reliable finding when the cases lead to the similar results. This issue is referred to as literal replication by Yin (2003) which suggests using different data sources for enhancing data credibility (Baxter and Jack 2008).

The data sources required for the case studies include corporate archive, interviews and some observations that are used to address the main research problem; to what extent concurrent NPD can reduce the time to market. The final output of the case studies is the NPD processes modeled by a GERT network.

In this section, two NPD cases are investigated which provide ideal platform to apply the methodology outlined. By analysing the practical application of the proposed GERT model, detailed and intensive knowledge of its use in modelling an overlapped NPD process can be obtained. The reasons behind choosing the companies are their fitting sequential NPD process and the potential to help evaluating a concurrent methodology as an attempt to reduce time to market. In what follows, the two cases are first introduced and then the proceeding steps of case study research are outlined.

The first case, FutureDesign™ is a platform NPD firm based in Dublin specialising in both the design and development of wide range of consumer products. Their portfolio extends from work with Daigeo on alcoholic beverage containers to the redesign of a number of products for the precast concrete industry in China. The firm specializes in medium to high technological uncertain assembly projects, as defined by Shenhar's (2001) orthogonal framework of project definition; including one-off part production, improvements to existing products, new-to-world products and concept development. Projects are progressed and coordinated organically within one internal project group in a rather informal way, where technological problems are resolved through extensive levels of communication within the project. The firm also operates a deliberate multiproject strategy and process that shares information and technology across multiple portfolio projects. Essentially, firm's core capability concerns the flexible process within their platform that allows products to be tailored to the needs of the customer. While the firm employs a purely sequential development process, it guarantees efficiency by ensuring that different divisions collaborate intensively to design parts of a product. Nevertheless, concurrent engineering has the potential to emerge as a driving force for future development and efficiency within the firm. For the purpose of this research, we will concentrate on a single product platform among multiple product lines.

Alhavipharma is the second company chosen to explore concurrent NPD in context using their projects data. It is a pharmaceutical company located in Tehran that possesses the largest share of export in pharmaceutical products. Fifty years of experience in producing new medicines based on internationally-registered formulations makes it a recognized case of NPD practices in its industry. Their portfolio includes licensed pharmaceutical productions, excipient material imports, and new medicine productions. The latter would fit the purpose of this research as it is currently a sequential process with lengthy completion time that might be reduced by concurrent practices. Investigating the proposed method in a whole different industry ensures that the approach is studied comprehensively which allows for various practical issues to be revealed and comprehended.

The data gathered from NPD processes were multifaceted and employed in the GERT model in a number of ways. We calculated activity durations using secondary research from the firms' existing timesheets. The secondary research consisted of the synthesis of existing data on activity durations from previous projects for a single project platform. The dada in relation to FuturaDesign™ and Alhavipharma, which were established from the existing timesheets, are shown in Appendices C and D, respectively.

During the course of our research, we relied on a series of semi-structured interviews with core staff members involved in each stage to the projects. Through consultation with the engineers and designers interviewed, we established the intercommunication transfers between coupled activities, the complexity of the activities, and the experience and skill level of the employees involved. Moreover, our semi-structured interviews established values for network variables as shown in Table 1.

Our study ignored the external integration variables and the influence of customers and supply chain partners. Despite this, there is a considerable evidence that the effects of supplier integration on competitive capabilities and firm performance are mixed (Koufteros, Vonderembse, and Jayaram 2005). We have also not considered both the linkages or leveraging between different product lines or technologies which may contribute to overall improved network efficiencies.

Table 1. *Primary Research Network Variables*

QUESTION	Purpose of Question	Measure	Variable
1	Employee Role in NPD Process	Activity	n/a
2	Experience of Employee	Likert Scale	b
3	Complexity of Task	Likert Scale	a
4	Activity information Dependence	Activity	n/a
5	Degree of Dependence	Likert Scale	a_{ij}
6	Duration of Fast Evolution	Hour(s)	p_{ij}

We found senior designers and engineers typically demonstrated 5 years of experience with highly experienced staff members demonstrating 10 years or greater, depending on the activity.

The process of decomposition involved developing Work Breakdown Structures (WBS) of the existing NPD processes. The WBS is a deliverable-orientated hierarchy of the work to be executed by the project team, in order to accomplish the project objectives and create the required deliverables (PMI 2008).

The WBS of FuturaDesign™ shown in Figure 3 follows a twelve stage milestone process with four major deliverables: business case, design and branding, prototype and patenting, and production. Likewise, the WBS of Alhavipharma is illustrated in Figure 4.

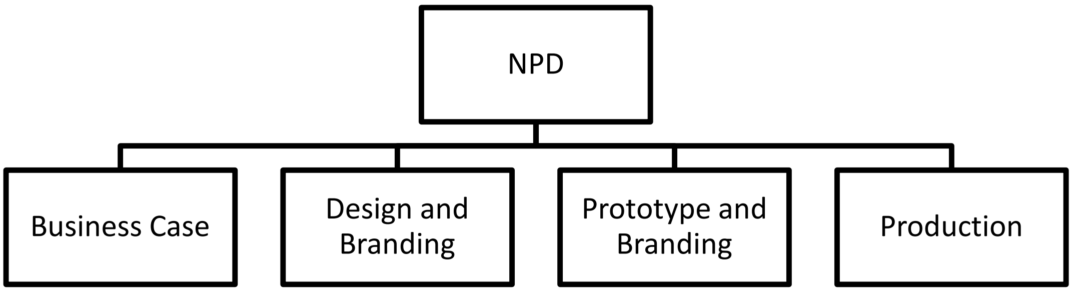


Figure 3. *FutureDesign™,'s WBS*

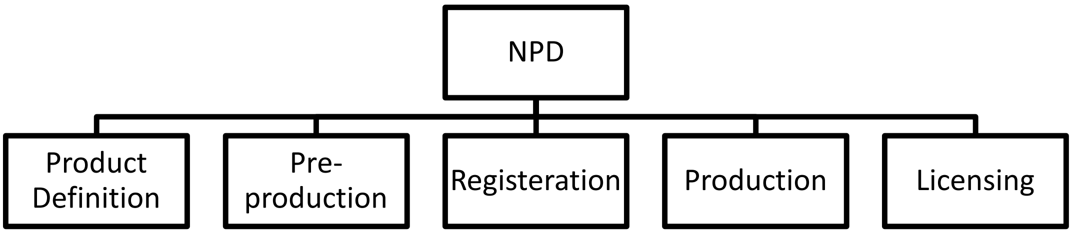


Figure 4. *Alhavipharma's WBS*

To examine the impact of concurrency on schedule performance and provide a basis for comparison, we first examined the existing sequential NPD processes using GERT. The time distributions for each activity were tested using the Anderson-Darling Goodness-of-Fit test to establish a specific time distribution function for each sample. The network constraints, the activity duration distribution functions, the information dependencies and feedback flows were characterised and modelled to companies' current sequential NPD processes. The sequential NPD models were replicated using Monte Carlo simulation and the results obtained compared with the corresponding existing projects.

A comprehensive flowchart in Appendix A demonstrates step-by-step case study design from selection to the conclusion of cases. This flowchart shows the sequence used in this research including the validation phases within different stages of the research.

4.2. Analyzing the Cases and Validation Methods

After gaining confidence in the sequential NPD model and Monte Carlo simulation, we then developed concurrent NPD processes using the methodology outlined in Section 2. The network constraints, the activity duration distribution functions, the information dependencies and feedback flows characterised in the sequential NPD processes remained consistent.

The overlapping of activities in the concurrent NPD processes was represented by the activity lag time, established as a percentage of the upstream activity, T_j, whereby;

$$T_{\text{lag}} = T_L . T_j \quad (4)$$

In turn, the rework probability function, p_{ij}, and the rework duration function, r_{ij}, were established for each activity in the concurrent NPD processes based on the information gathered. The network data for each activity for the first case fell under a number of headings, as shown in Table 2 The GERT networks of FuturaDesign™ and Alhavipharma are presented in Appendices F and E, respectively.

Table 2. *GERT Branch of FuturaDesign™*

Activity	Description	P_{ij}	Distribution	Time				Random Numbers		Z_r	X	Active	T_E
								R_1	R_2				
1-2	Market Research	1	Normal	$\mu =$	0.921	$\sigma =$	0.29		0.402	-0.247	0.85	1	0.85
1-3	Lag	1	Constant	$k =$	0.378						0.378	1	-0.47
3-4	Product Definition	1	Normal	$\mu =$	0.667	$\sigma =$	0.21		0.949	1.640	1.018	1	1.02
4-5	Rework Required	0.124	Function	$r_{ij} =$	0.058			0.848			0.058	0	0
4-5	No Rework Required	0.876	Constant	$k =$	0						0	1	0
3-6	Lag	1	Constant	$t_i =$	0.366						0.366	1	-0.65
6-7	Finance	1	Normal	$\mu =$	0.73	$\sigma =$	0.24		0.600	0.252	0.791	1	0.79
7-3	Feedback Financial Issues	0.2	Constant	$k =$	0			0.071			1.158	1	1.16
	No Feedback Required	0.8	Constant	$k =$	0						0	0	0
7-8	Rework Required	0.143	Function	$r_{ij} =$	0.093			0.126			0.093	1	0.09
7-8	No Rework Required	0.857	Constant	$k =$	0						0	0	0
6-9	Lag	1	Constant	$t_i =$	0.271						0.271	1	-0.52
9-10	Brand Development	1	Normal	$\mu =$	1.167	$\sigma =$	0.35		0.678	0.461	1.326	1	1.33
10-11	Rework Required	0.176	Function	$r_{ij} =$	0.108			0.720			0.108	0	0
10-11	No Rework Required	0.824	Constant	$k =$	0						0	1	0
9-12	Lag	1	Constant	$t_i =$	0.694						0.694	1	-0.63
12-13	Sales Channel	1	Normal	$\mu =$	5.238	$\sigma =$	1.11		0.479	-0.053	5.18	1	5.18
13-14	Rework Required	0.249	Function	$r_{ij} =$	0.158			0.631			0.158	0	0
13-14	No Rework Required	0.751	Constant	$k =$	0						0	1	0
12-15	Lag	1	Constant	$ti =$	2.848						2.848	1	-2.33
15-16	Product Design	1	Normal	$\mu =$	5.778	$\sigma =$	1.35		0.624	0.315	6.203	1	6.2
16-17	Rework Required	0.003	Function	$r_{ij} =$	0.006			0.320			0.006	0	0
16-17	No Rework Required	0.997	Constant	$k =$	0						0	1	0
15-18	Lag	1	Constant	$t_i =$	0.558						0.558	1	-5.64
18-19	Rapid Prototyping	1	Normal	$\mu =$	4.921	$\sigma =$	1.08		0.772	0.747	5.726	1	5.73
19-15	Feedback Assembly Issues	0.4	Constant	$k =$	0			0.166			6.284	1	6.28
	No Feedback Required	0.6		$k =$	0						0	0	0
19-20	Rework Required	0.661	Function	$r_{ij} =$	3.73			0.631			3.73	1	3.73
19-20	No Rework Required	0.339	Constant	$k =$	0						0	0	0
18-21	Lag	1		$t_i =$	0.535						0.535	1	-5.19
21-22	Testing	1	Normal	$\mu =$	0.825	$\sigma =$	0.34		0.537	0.093	0.857	1	5.19
22-15	Feedback Design Issues	0.5	Constant	$k =$	0			0.372			6.284	1	6.28
22-18	Feedback Material	0.12	Constant	$k =$	0						5.726	0	0
	No Feedback Required	0.38		$k =$	0						0	0	0
22-23	Rework Required	0.067	Function	$r_{ij} =$	0.595			0.158			0.595	0	0
22-23	No Rework Required	0.933	Constant	$k =$	0						0	1	0
2425	Product Evaluation	1	Normal	$\mu =$	0.706	$\sigma =$	0.17		0.765	0.721	0.831	1	0.83
25-26	Intel. Property Protection	1	Normal	$k =$	0						0	1	0
26-24	Feedback Registration Issues	0.1	Constant	$k =$	0			0.435			0.831	0	0
	No Feedback Required	0.9		$k =$	0						0	1	0
27-28	Product Outsourcing	1	Normal	$\mu =$	11.38	$\sigma =$	2.25		0.118	-1.187	8.704	1	8.7
30-31	Pilot Launch	1	Constant	$k =$	0						0	1	0
31	Launch	1	Constant	$k =$	0						0	1	0
												T_E	37.9

From now on, we mostly focus on the first case FuturaDesign™. However, some important findings in relation to the second case Alhavipharma are also mentioned toward the end of this section. There were five feedback flows in the first case where downstream activities provided information to upstream activities on errors or omissions found within the project. The feedback of financial issues between node 4 and node 2 represents unfeasible concept design decisions made during product definition. Similarly, the feedback of assembly issues between node 8 and node 6 represents errors made during the design stage. Node 9 contained two feedback flows found after testing; material issues and design issues. The final feedback flow represented issues with regard to intellectual patenting protection and the probability that the final design may require revising. The probabilities associated with the feedback flows were drawn from the data gathered. Each of the feedback flows are assumed to have zero time, that is, once errors are found the feedback of information is instantaneous.

The method of modelling the Monte Carlo simulations involved Microsoft Excel™'s macro Visual Basic Editor and the algorithm used is shown in Appendix B. A sample size of 10,000 replications was adequate for projects of such sizes and level of accuracy required (Moder, Phillips, and Davis 1983; Crandall 1976).

To improve the validity of our data and reduce the sample variance to a desired accuracy, the variance reduction technique of Antithetic Variables was employed. The Antithetic Variables method implies the use of two identical models with negative covariance used to generate a sample average between them. Essentially, the method exploits the fact that the standard normal random variable or z-score is distributed about a mean of zero, a variance of one, and is symmetrical. Finally, we validated our GERT Monte Carlo simulation model ensuring consistency and validity between runs. In order to validate our model, the results were tested against the null-hypothesis. The Kolmogorov-Smirnov and the Chi-Square Goodness-of-Fit tests were used to tests the data and are most suitable for large sample sizes.

4.3. Case Study Results

The performance measure of greatest interest within our results was the comparison of the project lead times between the existing sequential NPD process and the new concurrent NPD process. The sample mean project lead times for the sequential and the concurrent NPD processes were 43.55 days and 31.46 days, respectively. This indicates that the overlapped NPD process results in a sample mean saving of 12.09 days or 27.8 percent on the project lead time as evident in Figure 5, indicating Probability against the Project Duration.

The results of an activity duration-based sensitivity analysis were analyzed with the degree of change in project lead time measured using Common Random Numbers (CRN). The CRN approach tests all scenarios under the same conceptual experimental conditions and the difference in the performance measure for both the concurrent and the sequential models are computed for each replication. The mean sensitivity (or change in project lead time), Z, for each activity following a sensitivity analysis of 20% in activity durations is shown in Figure 6.

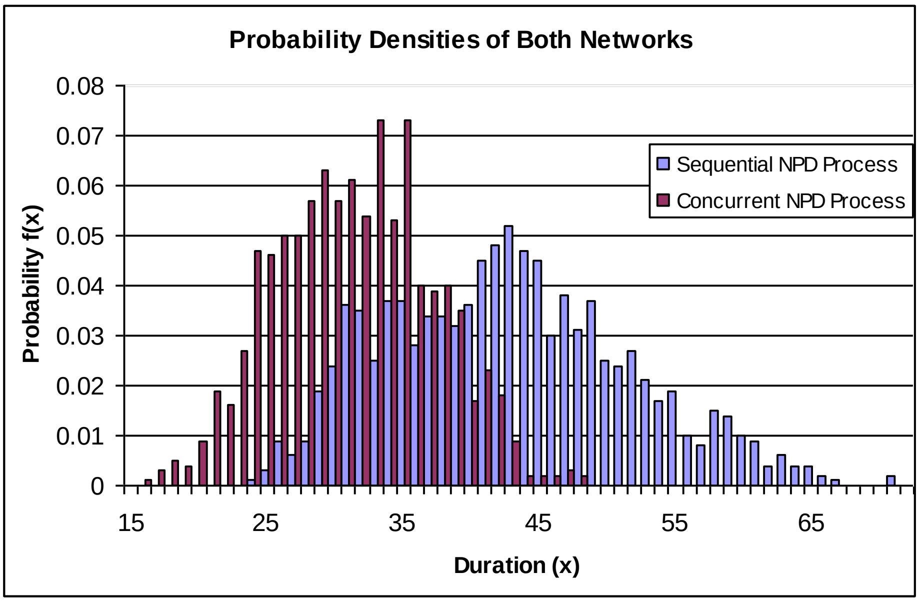


Figure 5. *GERT Branch of FuturaDesign*^{TM}

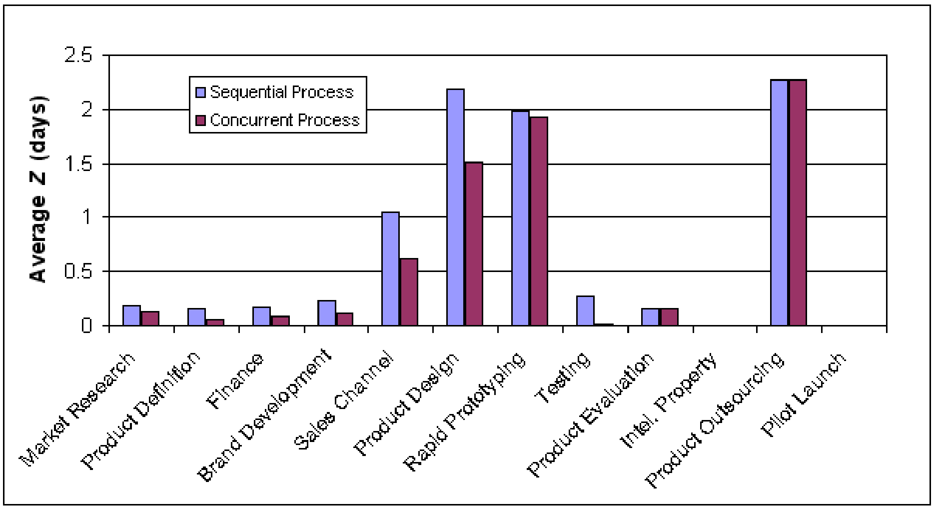


Figure 6. *Project Lead Time Change with Activity Duration Sensitivity Analysis*

As expected, activities that were not overlapped in the concurrent NPD process computed corresponding durations to the sequential NPD process, namely; Product Evaluation, and Product Outsourcing. However, in general the results shown for concurrent activities indicated that concurrent engineering resulted in an apparent desensitization or reduced sensitivity for certain activities, namely; Market Research, Project Definition;

Finance; Sales Channel; Product Design; and Testing. Given that CRN was carried out, we wonder what causes the apparent desensitization of activity durations.

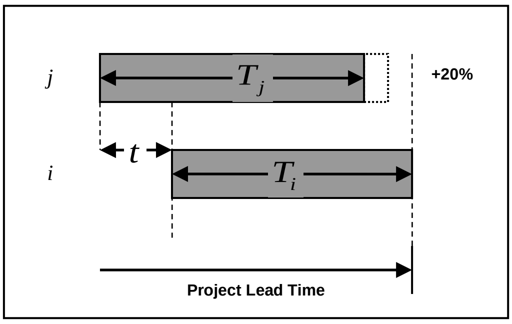


Figure 7. *Overlapped Activities*

Consider the overlapped activities (activity i and j) shown in Figure 7, where activity i releases information to activity j at lag time t. When applying a 20% increase to activity j, the extended activity duration has no overall effect on the estimated project lead time. Intuitively, by increasing the activity duration of an overlapped activity, the amount of rework required with respect to Eq. (2) will in turn increase proportionately. However, this extended rework time is leveraged by a decrease in the probability of rework occurring, with respect to Eq. (1). In the case of activities that are not on the critical path, an additional buffer can be generated as a result of concurrency by absorbing potential changes or activity rework. As a result, it was found that concurrent engineering can desensitize activity durations in certain circumstances, leading to a reduced sample variance.

The sensitivity analysis was in turn extended to employee experience using CRN between the two processes. As shown in Figure 8, the Concurrent Process demonstrates a greater reduction in project lead time when employee experience was increased by 20% for each activity. This occurs as both the probability for, and duration of, rework occurring reduces as a result of increases in employee experience. Accordingly, our model shows that increases in human resources are more effective and better spent in the Concurrent Process.

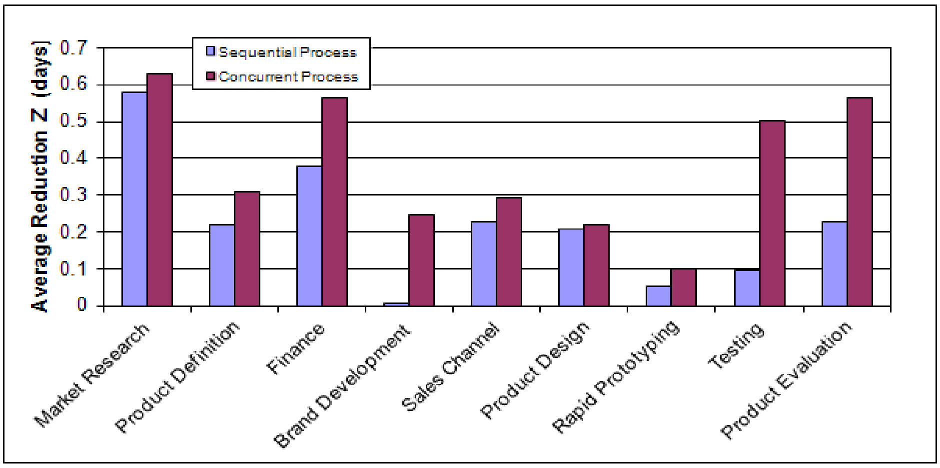


Figure 8. *Reduced Project Lead Time Change with Experience Sensitivity Analysis*

In relation to the second case Alhavipharma, it was found that the mean project lead times for the sequential and the concurrent NPD processes were 348.18 days and 292.17 days, respectively, which indicates 19.2 percent saving on the project lead time using the concurrent approach.

5. Conclusion

The primary objective of this paper was to explore the problem of modelling concurrent NPD processes through the use of the GERT scheduling approach and then apply the model to some practical cases. Through this research, we proposed a time-computing GERT model whose objective is to estimate the project completion time by acquiring the dynamic and complex characteristics of information flows in a concurrent NPD process. Our GERT method, proposed in this paper, resolves these coordination complexities in a number of ways: firstly, the graphical representation of the overlapped NPD process provides the modeller with a holistic representation of the network incorporating communication and information flows. The rework principle and the increased levels of communication as a result of overlapping are two of the most complex features in concurrent NPD processes. Our model addresses both of these issues in an explicit manner, while employing previous research on the probability and duration of activity rework. The model allows for the inclusion of human factors through coordination and communication variables such as the degree of information dependence, the experience of the human resources, and the complexities of the tasks. Secondly, our method provides managers with an unambiguous and comprehensive flow diagram of all necessary communications flows and information transfers within the NPD process.

This work provides project managers with an intuitive feel for what to do in the presence of risk factors in an environment whose outcome is uncertain. Moreover, our model indicates what information transfer needs to be communicated and when. Our communication lines may also be considered as project review points, encompassing Dragut and Bertrand's (2008) hierarchical performance structure for NPD projects. Furthermore, the GERT model allows the modeller to test varying levels of quality improvement by increasing the average experience level or in turn, alternating between different multifunctional project teams. As a result, the proposed GERT model can identify the necessary parameters to achieve a successful concurrent strategy.

Our approach to modelling the case studies was straightforward. We first modelled the current sequential NPD processes of two companies from diverse industries which allowed us to contrast any alternative process strategy whilst using variance reduction techniques. We successfully established network characteristics through the analysis of existing platform information and the synthesis of semi-structured interviews. Besides, the activity complexity and degree of dependence between activities were also recognized. We found a high level of experience leveraged the rework priori of a number of activities. This enabled us to strategically identify any cost-saving benefits, project lead time reductions or risk mitigating features and provided managements at the companies with realistic figures which advocated the implementation of an alternative process strategy. Our findings indicated a reduction of 23.5 percent to current project lead time on average for both companies. In turn, through the application of our model we found that increases in human resources are more cost-effective within a concurrent process.

This research comes to an end by suggesting six future research directions according to the limitations of the research. Our model focuses primarily on minimizing the total expected project completion time. We are not considering the product quality as a result of overlapping. Future research may adapt the proposed GERT model to consider process queuing using Q-GERT and the effect overlapping has on quality development. In addition, resource levelling was not investigated within our case study, and we did not consider scenarios whereby resource demand exceeded resource availability. In resource-constrained project scheduling, the issue of overallocation of project resources becomes more apparent when concurrent engineering is applied. A firm may also need to hire more designers, engineers and project managers to achieve overlapping results and coordinate the network activities. Future research could extend the *fast evolution* strategy to consider the resource levelling of specific resources in NPD projects in proportion to the degree of activity overlap. This could be achieved through the use of our proposed GERT model and identifying scenarios where activity overlapping should or should not be used. Our transition and probabilities remain constant between each rework phase, in reality however, the designer will gain some experience from the initial rework and both the rework duration and probability will decrease, respectively. Accordingly, Markov Chain Monte Carlo simulation could be used to supplement our model. Our model and case study focused primarily on platform NPD processes whereby, existing network information was used to represent the system. In radical NPD process, network information may not be readily available or may only be partly known initially. As such, future research may adapt the model to Fuzzy GERT processes.

References

Aytulun, SK, and AF Guneri. 2008. "Business process modelling with stochastic networks." International Journal of Production Research 46 (10):2743-64.

Azaron, Amir, Hideki Katagiri, and Masatoshi Sakawa. 2007. "Time-cost trade-off via optimal control theory in Markov PERT networks." Annals of Operations Research 150 (1):47-64.

Azaron, Amir, Hideki Katagiri, Masatoshi Sakawa, Kosuke Kato, and Azizollah Memariani. 2006. "A multi-objective resource allocation problem in PERT networks." European Journal of Operational Research 172 (3):838-54.

Baxter, Pamela, and Susan Jack. 2008. "Qualitative case study methodology: Study design and implementation for novice researchers." The qualitative report 13 (4):544-59.

Bellas, Carl J, and A Coskun Samli. 1973. "Improving New Product Planning with GERT Simulation." California management review 15 (4):14-21.

Brooks, Frederick P. 1975. The Mythical Man-onth: Essays on Software Engineering, Anniversary Edition. MA: Addison-Wesley Reading.

Browning, Tyson R, and Steven D Eppinger. 2002. "Modeling impacts of process architecture on cost and schedule risk in product development." Engineering Management, IEEE Transactions on 49 (4):428-42.

Carrascosa, Maria, Steven D Eppinger, and Daniel E Whitney. 1998. Using the design structure matrix to estimate product development time. Paper presented at the Proceedings of the ASME design engineering technical conferences.

Cooper, Robert Gravlin. 2001. Winning at new products: Accelerating the process from idea to launch. 3rd ed. Cambridge: Perseus Publishing.

Crandall, Keith C. 1976. "Probabilistic time scheduling." Journal of the Construction Division 102 (3):415-23.

Dragut, Andreea B, and J Will M Bertrand. 2008. "A representation model for the solving-time distribution of a set of design tasks in new product development (NPD)." European Journal of Operational Research 189 (3):1217-33.

Drezner, Stephen M, and A Alan B Pritsker. 1965. "Use of Generalized Activity Networks in Scheduling." In.: Defense Technical Information Center.

Flyvbjerg, Bent. 2006. "Five misunderstandings about case-study research." Qualitative inquiry 12 (2):219-45.

Ford, David N, and John D Sterman. 2003. "Overcoming the 90% syndrome: Iteration management in concurrent development projects." Concurrent Engineering: Research and Applications 11 (3):177-86.

Jones, Tim. 1997. New product development: an introduction to a multifunctional process. 1st ed. Oxford: Butterworth-Heinemann.

Koufteros, Xenophon, Mark Vonderembse, and Jayanth Jayaram. 2005. "Internal and external integration for product development: the contingency effects of uncertainty, equivocality, and platform strategy." Decision Sciences 36 (1):97-133.

Krishnan, Viswanathan. 1996. "Managing the simultaneous execution of coupled phases in concurrent product development." IEEE Transactions on Engineering Management 43 (2):210-7.

Krishnan, Viswanathan, Steven D Eppinger, and Daniel E Whitney. 1995. "Accelerating product development by the exchange of preliminary product design information." Journal of Mechanical Design 117 (4):491-8.

Krishnan, Viswanathan, Steven D Eppinger, and Daniel E Whitney . 1997. "A model-based framework to overlap product development activities." Management science 43 (4):437-51.

Lévárdy, Viktor, and Tyson R Browning. 2009. "An adaptive process model to support product development project management." Engineering Management, IEEE Transactions on 56 (4):600-20.

Moder, J J, C R Phillips, and E W Davis. 1983. Project management with CPM, PERT and precedence diagramming. 3rd ed. New York: Van Nostrand Reinhold.

Moore, L J, and E R Clayton. 1976. GERT Modelling and Simulation Fundamentals and Applications. 1st ed. USA: Mason/Charter Publishers Inc.

Peña-Mora, Feniosky, and Michael Li. 2001. "Dynamic planning and control methodology for design/build fast-track construction projects." Journal of construction engineering and management 127 (1):1-17.

PMI. 2008. A Guide to the Project Management Body of Knowledge: PMBOK® Guide. 4th ed: Project Management Institute, Incorporated.

Pontrandolfo, Pierpaolo. 2000. "Project duration in stochastic networks by the PERT-path technique." International Journal of Project Management 18 (3):215-22.

Pritsker, A Alan B. 1966. GERT: Graphical evaluation and review technique. California: Rand Corporation.

Pritsker, A Alan B, and W W Happ. 1966. "GERT: Graphical Evaluation and Review Technique, Part I. Fundamentals." Journal of Industrial Engineering 17 (5):267-74.

Pritsker, A Alan B, and G E Whitehouse. 1966. "GERT: Graphical Evaluation and Review Technique, Part II. Applications." Journal of Industrial Engineering 17 (5):293-301.

Roemer, Thomas A, and Reza Ahmadi. 2004. "Concurrent crashing and overlapping in product development." Operations Research 52 (4):606-22.

Roemer, Thomas A, Reza Ahmadi, and Robert H Wang. 2000. "Time-cost trade-offs in overlapped product development." Operations Research 48 (6):858-65.

Shenhar, Aaron J. 2001. "One size does not fit all projects: exploring classical contingency domains." Management science 47 (3):394-414.

Smith, Robert P, and Steven D Eppinger. 1997. "Identifying controlling features of engineering design iteration." Management science 43 (3):276-93.

Smith, Robert P, and Jeffrey A Morrow. 1999. "Product development process modeling." Design studies 20 (3):237-61.

Tang, Dunbing, Guangjun Zhang, and Sheng Dai. 2009. "Design as integration of axiomatic design and design structure matrix." Robotics and Computer-Integrated Manufacturing 25 (3):610-9.

Taylor III, Bernard W, and Laurence J Moore. 1980. "R & D project planning with Q-GERT network modeling and simulation." Management science:44-59.

Terwiesch, Christian, and Christoph H Loch. 1999. "Measuring the effectiveness of overlapping development activities." Management science 45 (4):455-65.

Wang, Juite, and Yung-I Lin. 2009. "An overlapping process model to assess schedule risk for new product development." Computers & industrial engineering 57 (2):460-74.

Wu, Desheng Dash, Xie Kefan, Chen Gang, and Gui Ping. 2010. "A risk analysis model in concurrent engineering product development." Risk Analysis 30 (9):1440-53.

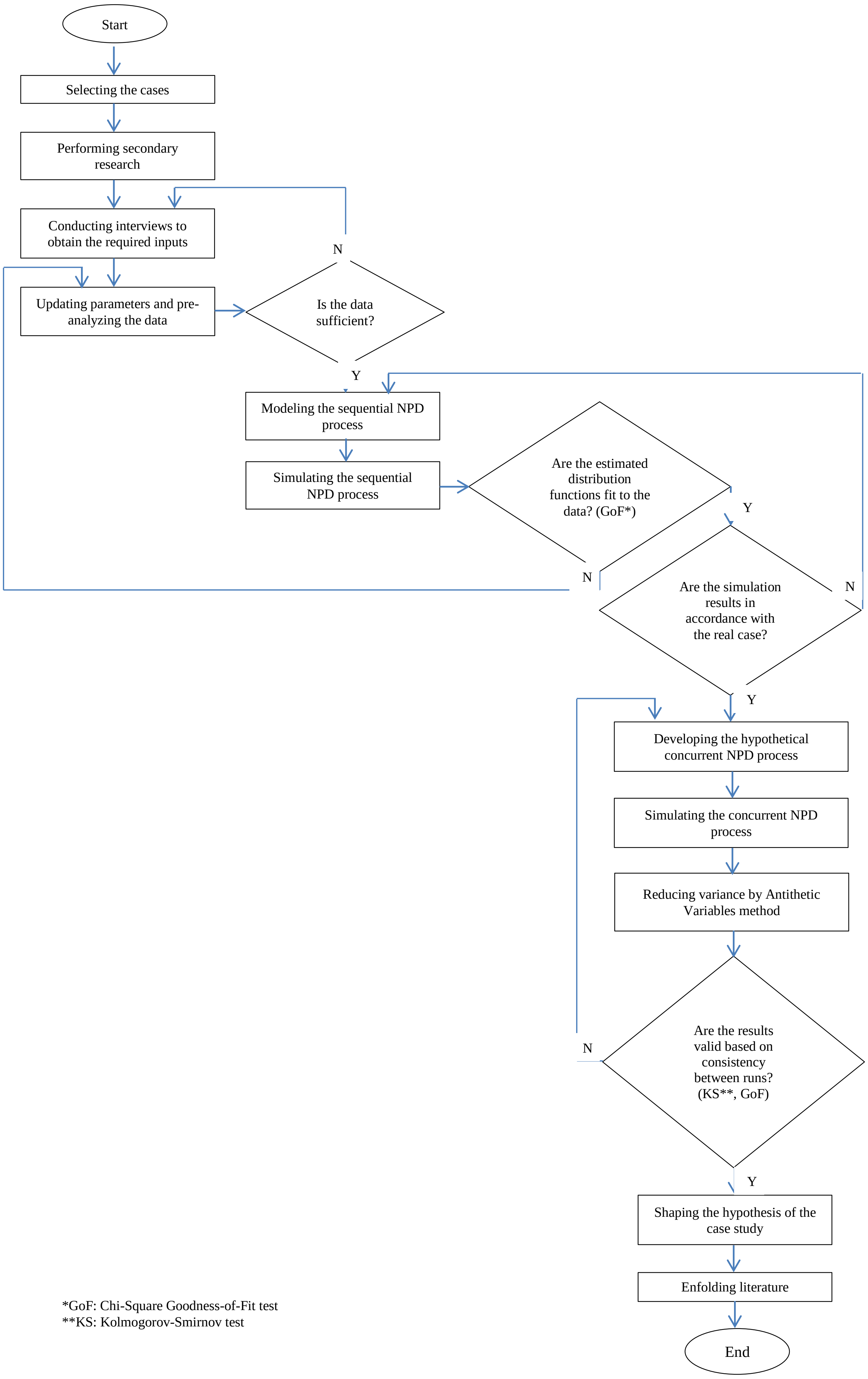
Yan, Hong-Sen, Bin Wang, Duo Xu, and Zheng Wang. 2010. "Computing completion time and optimal scheduling of design activities in concurrent product development process." IEEE Transactions on Systems, Man and Cybernetics Part A: Systems and Humans 40 (1):76-89.

Yan, Ji-Hong, and Cheng Wu. 2001. "Scheduling approach for concurrent product development processes." computers in Industry 46 (2):139-47.

Yi-song, Zheng, Li Dong, and Zhao Feng. 2009. Study on a GERT based method for hi-tech product development project planning. Paper presented at the 2009 16th International Conference on Industrial Engineering and Engineering Management.

Yin, Robert K. 2003. Case Study Research: Design and Methods: SAGE Publications.

APPENDIX A



*GoF: Chi-Square Goodness-of-Fit test
**KS: Kolmogorov-Smirnov test

APPENDIX B

```
(General)
Sub Critical()
Dim counter As Integer
For counter = 1 To 10000
Calculate
Let k = counter + 10
Cells(k, 23).Value = Cells(50, 15).Value
Next counter
End Sub
```

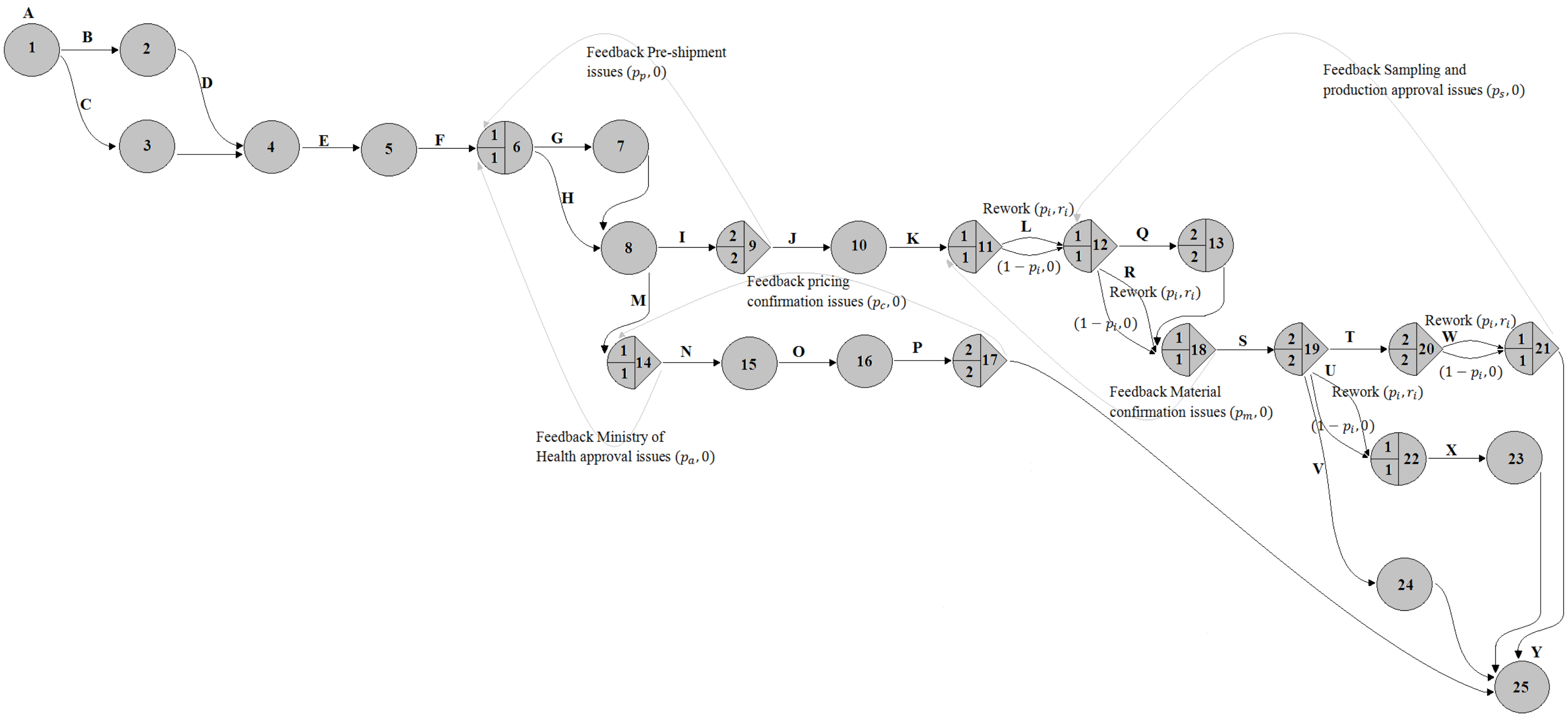
APPENDIX C

Activity	Employee	Likert Scale (1-5)		Information Dependence	Probability of Feedback	Fast Evolution day(s)
		Experience	Activity			
Market Research	001	5/5	4/5	n/a	n/a	0.50
	002	3/5	3/5	n/a	n/a	0.29
	006	5/5	3/5	n/a	n/a	0.57
	007	3/5	4/5	n/a	n/a	0.29
	Average	**4/5**	**3.5/5**	**n/a**	**n/a**	**0.41**
Product Definition	001	4/5	3/5	3/5	n/a	0.43
	002	3/5	2/5	2/5	n/a	0.29
	005	2/5	2/5	2/5	n/a	0.21
	006	5/5	4/5	3/5	n/a	0.14
	008	5/5	3/5	2/5	n/a	0.14
	Average	**3.8/5**	**2.8/5**	**2.4/5**	**n/a**	**0.24**
					Product Definition	
Project Finance	001	4/5	3/5	4/5	0.10	0.14
	002	3/5	3/5	5/5	0.30	0.29
	007	3/5	4/5	3/5	0.30	0.29
	008	5/5	4/5	4/5	0.10	0.29
	Average	**3/5**	**3.5/5**	**4/5**	**0.20**	**0.25**
Brand Development	001	4/5	4/5	2/5	n/a	0.57
	002	3/5	3/5	1/5	n/a	0.71
	005	2/5	3/5	3/5	n/a	0.71
	006	5/5	4/5	3/5	n/a	0.43
	Average	**3.5/5**	**3.5/5**	**2.25/5**	**n/a**	**0.61**
Develop Sales Channel	001	4/5	2/5	1/5	n/a	2.50
	002	3/5	3/5	2/5	n/a	3.00
	007	3/5	3/5	2/5	n/a	3.00
	008	5/5	4/5	3/5	n/a	3.00
	Average	**3/5**	**3/5**	**2/5**	**n/a**	**2.88**
Product Design	002	3	5	1/5	n/a	0.57
	005	2	5	0/5	n/a	0.43
	006	5	5	0/5	n/a	0.57
	Average	**3.3/5**	**5/5**	**0.2/5**	**n/a**	**0.52**
					Product Design	
Rapid Prototyping	002	3	3	5/5	0.40	0.50
	003	2	3	4/5	0.50	0.29
	004	2	4	5/5	0.50	0.50
	005	2	3	5/5	0.20	0.57
	Average	**2.25/5**	**3.25/5**	**4.75/5**	**0.40**	**0.46**
					Product Design; Prototyping	
Testing	003	2	3	5/5	0.6; 0.2	0.29
	004	1	4	4/5	0.5; 0.05	0.29
	005	2	3	4/5	0.4; 0.1	0.25
	Average	**1.6/5**	**3.3/5**	**4.33/5**	**0.5; 0.12**	**0.27**
Evaluate Prototype	003	2	2	3/5	n/a	n/a
	004	1	4	4/5	n/a	n/a
	005	2	3	4/5	n/a	n/a
	008	5	3	3/5	n/a	n/a
	Average	**2.5/5**	**3/5**	**3.5/5**	**n/a**	**n/a**
Product Outsourcing	001	4	5	4/5	n/a	n/a
	002	3	4	4/5	n/a	n/a
	006	5	3	4/5	n/a	n/a
	007	3	4	5/5	n/a	n/a
	008	5	4	3/5	n/a	n/a
	Average	**4/5**	**4/5**	**4/5**	**n/a**	**n/a**

APPENDIX D

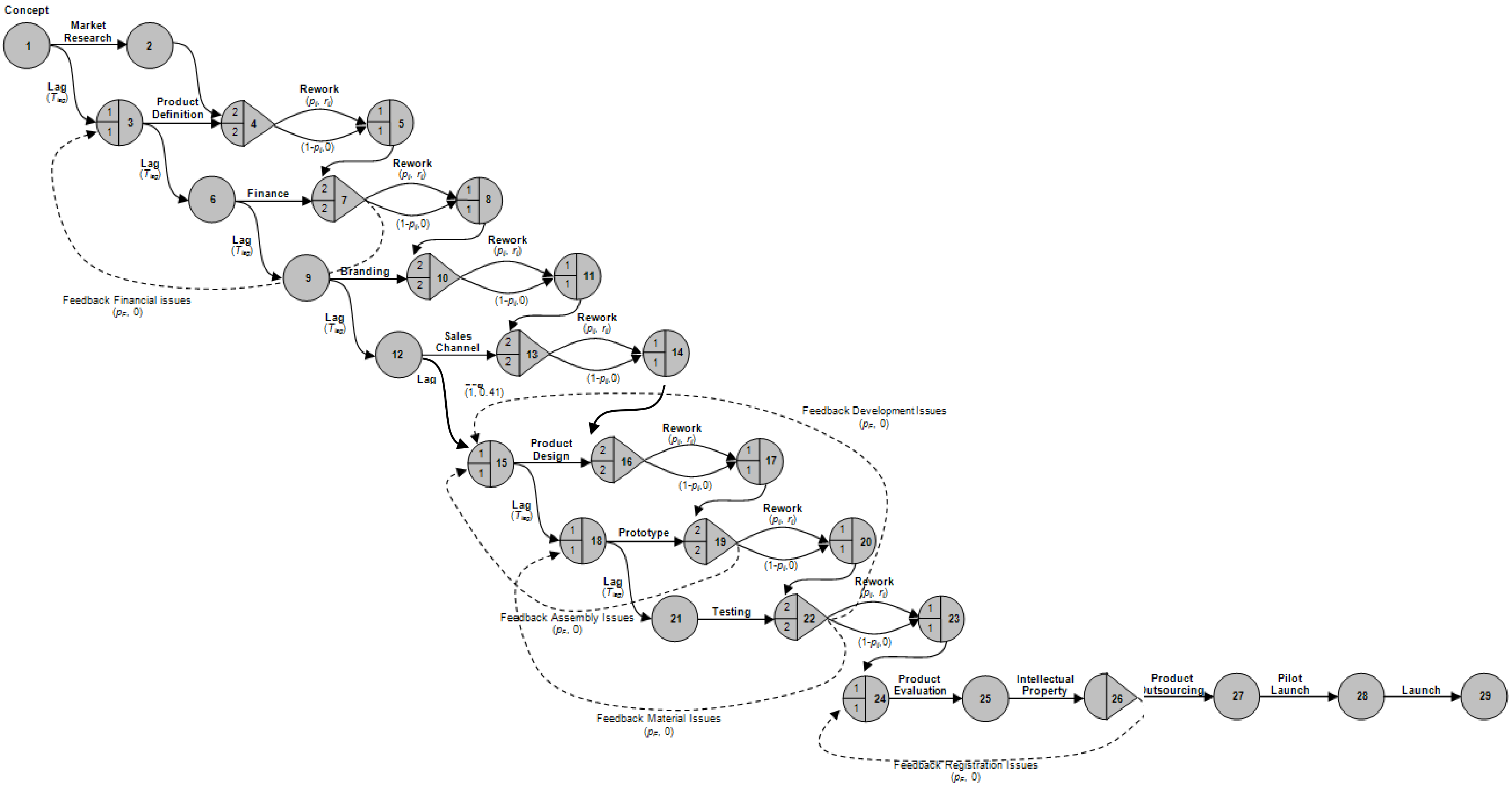
Phase	No.	ID	Activity/Milestone	Duration	Predecessors	Rework	Feedback
Product Definition	1	A	New medicine suggestion	0	-		
	2	B	Pre-marketing	15	1		
	3	C	Name registration	1	1		
	4	D	Effective substance procurement	31	2		
	5	E	Registration in Iran Drug List	46	4		
	6	F	Experimental formulation	7	5		
Pre-production	7	G	Auditing producer and contracting	61	6		
	8	H	Ordering materials	31	6		
	9	I	Receiving materials pre-shipment	8	8,7		7,8
	10	J	Sending purchase order	31	9		
	11	K	Payment and procuring the materials	8	10		
	12	L	Customs clearance and warehousing	12	11	x	
Registration	13	M	Getting MOH approvals	21	8,7		7,8
	14	N	Getting IR medicine organization approvals	11	13		
	15	O	Getting Iran code and barcode from MOC	31	14		
	16	P	Pricing confirmation	31	15		14
Production	17	Q	Providing materials, batch sheet and production method	6	12		
	18	R	Materials confirmation experiments	25	12	x	12
	19	S	Scale-up and production batch record	7	17,18		
	20	T	Secondary packaging and IPQC	3	19		
	21	U	Comprehensive records documentation	7	19	x	
	22	V	Outsourcing In-vivo and In-vitro experiments	15	19		
Licensing	23	W	Sampling and getting MOH approvals for production	22	20	x	17
	24	X	License accreditation	15	21		
	25	Y	Developed New Product	0	16,22,23,24		

APPENDIX E



A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Feedback Pre-shipment issues $(p_p, 0)$
Feedback Sampling and production approval issues $(p_s, 0)$
Rework (p_i, r_i)
$(1 - p_i, 0)$
Feedback pricing confirmation issues $(p_c, 0)$
Feedback Material confirmation issues $(p_m, 0)$
Feedback Ministry of Health approval issues $(p_a, 0)$

APPENDIX F



Concept
Market Research
Lag
Product Definition
Rework
Finance
Branding
Feedback Financial issues
Sales Channel
Lag
(1, 0.41)
Feedback Development Issues
Product Design
Prototype
Testing
Feedback Assembly Issues
Feedback Material Issues
Product Evaluation
Intellectual Property
Product Outsourcing
Pilot Launch
Launch
Feedback Registration Issues