A General Framework for Controlling Time
Constrained NPD Projects
A.B. Dragut¹, J.W.M. Bertrand²

Abstract
Using recent empirical studies, we formulate a general framework of the hierarchical control processes needed for managing a new product development (NPD) project with a high technological uncertainty, under tight time constraints. Considering the project delivery time and resources as given, the project and its control are organized to solve the uncertainty in the new product specifications through repeated internal adjustments and interactions with customers. Our framework integrates the uncertainty regarding both the market requirements and technological uncertainties. They lead to the addition/deletion of design tasks, and to a stochastic solving time of the design tasks.

The paper contributes to the area of NPD work organization models, and to the development of management-related NPD project control concepts, both areas presenting research opportunities according to Brown, Eisenhardt (1995).

Keywords: new product development, project management, modelling.

1 Introduction
This paper introduces a general framework for managing NPD projects with a high technological uncertainty under tight time constraints. This framework allows the product definition to evolve after the beginning of the detailed design phase. The paper addresses the quality, time and resource characteristics of NPD projects from a conceptual, and modelling point of view. As in Ulrich, Eppinger (2000) we use the term product specifications for the key product design variables. We introduce new concepts for the design tasks internal structure, as well as measures of their relative importance for realizing the product specifications. By a frequent NPD project progress evaluation, these concepts allow either an optimal adjustment of product specifications, given the resources remaining until project deadline, or a project abandonment. The last situation occurs when either the project exceeds its budget or cannot longer meet the minimal requirements regarding the product specifications. Introducing concepts formalizing the quality-time trade-off in the product specifications, the paper contributes to the development of management-related control concepts in the NPD projects, an area presenting research opportunities according to Brown, Eisenhardt (1995). The proposed model has three levels: aggregate decision, detailed planning, and execution. The framework is intended to guide the management scientist formulation of NPD process stochastic models. Similar

¹Dept. of Operations Planning and Control, Faculty of Technological Management, Eindhoven University of Technology, 5600MB Eindhoven, The Netherlands (e-mail: {a.b.dragut@tm.tue.nl})
²Dept. of Operations Planning and Control, Faculty of Technological Management, Eindhoven University of Technology, 5600MB Eindhoven, The Netherlands
frameworks have been previously developed for production processes in Dempster et al. (1981), and Hackman, Leachman (1989).

Section 2 presents a historical perspective on NPD project control methods. Section 3 describes a hierarchical control model with multiple review periods, which evaluates the NPD project progress and integrates the uncertainty regarding the product specifications, the design tasks, and the time needed for realizing the project. The model is based on accepted scientific knowledge on product innovation, quality deployment function, design activities definition, concurrent engineering, project structuring and management. In section 4 we define the model elements that play a role in the control framework. They will be used in the mathematical modelling of the decision processes in the hierarchical control structure of the framework. This mathematical model will be presented in a subsequent paper (Dragut, Bertrand, 2002). The section 5 concludes the paper.

2 Historical perspective on NPD projects research

In the project planning and control literature, the breakthrough that led to the Program Evaluation and Review Technique in 1958 has been followed by many additions and revisions. In the early PERT system descriptions, the PERT network was updated on a regular basis. This allowed a formal process of status updating of all tasks scheduled to be started, or completed during the prior period, of producing new time estimates for future tasks, as well as the re-design process. According to DOD/NASA PERT/Cost Guide (1962), the current plan revision in the PERT/COST System updated the precedence relationships and/or the content (deletion and/or addition of tasks to the network) of the network. Later, in the project planning and control research the dominant concepts were the ones of:

- precedence: a fixed partial order on a fixed set of tasks for the entire project duration;
- time-cost task trade-off: task duration may be shortened, at a certain cost;
- task indivisibility: a task is a unity with start and finish times.

This explains why the various approaches to incorporate uncertainty in the project planning and control techniques (Elmaghraby 1995; Herroelen et al. 1998; Krishman, Ulrich 2001; Tavares 2002) viewed a task as a unity and addressed the uncertainty issue in the duration/flow of tasks. Explicit trade-offs in the product definition process in terms of design tasks to be performed did not appear, not even in the generalized activity networks approach (Elmaghraby 1995; Dawson, Dawson 1995), which assumed only an early partial product definition.

Empirical research of Tatikonda, Rosenthal (2000a) suggests that in many firms, NPD projects start with lax specifications of the new product requirements, which evolve during the project. This level of uncertainty may be far beyond what can be modeled by Beta probability density functions for the du-
ration of design tasks (PERT) and what can be modeled by probabilities that
design tasks will have to be redone (GERT) (Dawson, Dawson, 1998; Oorschot
2001). Bhattacharya et al. (1998) formalizes trade-offs underlying the new prod-
uct definition process emphasizing the uncertainty caused by a highly dynamic
market situation. However, their model does not consider the technological un-
certainty appearing inside the firm as the result of its own innovation process.

NPD projects with high technological product or process uncertainty are
referred to as experiential NPD projects (Eisenhardt, Tabrizi, 1995). Experien-
tial product development projects consists of uncertain, ill-defined, and unstable
design tasks. At the start of the project, it is uncertain which design tasks
are really necessary for realizing the product specifications and it is even un-
certain which (or the extent to which) product specifications can be realized at
a certain deadline. Their design tasks are often reorganized during execution,
and the product specifications of the product are gradually reconsidered, fact
sustained by numerous researchers (Dawson, Dawson,1998; review in Krishnan,
Ulrich, 2001).

3 A multiple review periods hierarchical NPD
control structure

A complete NPD project can be divided in a sequence of phases (Ulrich, Eppi-
ger, 2000). For the design process, we consider the definition of Doumeingts
et al. (1996): it translates customer/market requirements/specifications into a
product definition and a manufacturing process definition. Similarly to Mac-
Cormack et al. (2001), we distinguish three overlapping phases: the system
design/concept development (performing a first work breakdown from customer
needs into product specifications, and from product specifications into design
tasks), the detailed design phase (consisting of solving the design tasks), and
the system level test (integrating the solved design tasks result into a complete
system and tested) (see Figure 1.).

Figure 1.
The first and the last phase are too problem-dependent to be integrated in a
general mathematical framework of the operational process. Therefore, the aim
of this paper is to construct a dynamic model for the management of the time
and resource aspects of transforming the customer needs into detailed product
specifications during the detailed design phase, taking into account the overlap
of the other two phases.

During the concept development part, the initial system specifications are
set. They describe in precise, measurable terms what the product has to do.
With them starts both the development of a first work breakdown structure
(WBS) and the partitioning of each system specification into a self consistent
set of specifications for all the intended units, assemblies and modules of the
new product (i.e. a specification tree).

As in Aslaksen and Belcher (1992) and Shtub et al. (1994) we consider
the WBS as being a product-oriented tree, which consists of a number of levels, starting with the complete product, and progressing downwards through as many levels as are necessary to obtain design elements that can be assigned to and performed by one of the engineers. Once this is done, it is possible to arrange all its design elements in a network resembling a directed tree with a single root node. The elements on the lowest level are always completely described by: a complete task statement (i.e. what work has to be accomplished); an identification of the necessary prerequisites to start it; a detailed description of what the output or result of the work should be and in what form is to be presented (Aslaksen, Belcher 1992). Elements on higher levels may or may not have this property. The lowest level design elements are called design tasks.

To secure accountability through the design elements created by the WBS partitioning, a first specification tree will also be created (see Figure 2.). Thus, we assume in this paper a one to one correspondence between a design task and a product specification from the module level of detail (see Figure 2.).

Figure 2.

Later in time, more design tasks may emerge; design reviews are needed for mainly three reasons. First, no matter how uncertain is the project, design tasks have to be defined before its start, otherwise the WBS structure is not feasible (Shtub et al., 1994). So, in real life, the management of the project will be forced to specify some design elements by decomposing them into design tasks, without being sure that the work content of those design tasks reflects exactly the achievement of that design element. Thus, only for small periods of time during the detailed design phase, the relationships between design tasks as well as their number can be viewed as stable. Second, the product specifications and their refinements are established before knowing all the constraints that either the technology or the market places on what can or should be achieved at the design tasks level. Third, new design tasks may emerge as a result of the feedback from the system level tests.

Our NPD project control model performs decision/scheduling/execution cycles, each time taking into account the new surroundings it is facing. At the beginning of each new cycle, the state of the system is reviewed and updated by observing the technological knowledge accumulated at the engineering level, and by incorporating new information about customer needs. Thus, the uncertainty in the new product definition is decreased in time and this model structure allows the controller to adapt its decisions to changing conditions.

The planning and control problem at the beginning of each new cycle is hierarchically approached for mainly two reasons. First, by decomposition of the overall planning problem into several sub-problems, the complexity of the planning problem is reduced. Second, the effects of uncertainty regarding the structure and solving times of design tasks are split over the levels. Thus, hierarchical planning leads to a consistent and controllable planning problem. The decisions made at a higher planning level provide targets and restrictions to the lower level decision making.

Our approach to NPD projects is supported by the recent research in orga-
nization design of Haque et al. (2000). Their paper models and analyses the NPD project and organization in terms of tasks, teams, roles and communication links, relating the project hierarchy to the organization hierarchy. We assume in this paper similar project and resource levels (see Figure 3.), but for the internal structure of these levels we also use the research results of Oorschot (2001), which enables us to mathematically formulate the control problem of each of those levels.

The proposed control model of the NPD project is a discrete time one. The project will be reviewed at equidistant points in time until the deadline, $T$. The hierarchical structure proposed for each review period corresponds to a decision/scheduling/execution cycle, and consists of three levels: aggregate decision level, detailed planning level (rescheduling decision, scheduling), and engineering level.

4 Model Elements

Our NPD control structure has multiple review periods. Thus, the essential modelling assumptions are related to how we model the current knowledge about the NPD project at the beginning of each review period. To end up with a practical operational control framework, it is necessary to make the transition from a qualitative analysis dealing with concepts and structures, to a quantitative analysis in terms of measurable variables. We select a state variable set based on the significance of each variable in explaining some aspect of the product’s status during its development, and to their aggregate ability of conveying the product status at each point during its development. This set of variables contains indicators of the duration of the NPD project as well as of the cost, the quality and the market value of the new product.

In this section, we first give the exhaustive list of the key elements and assumptions embedded in the structure of the model. For each of them we present the connections with existing literature as well as indications of how their values can be computed. Thereafter, we briefly describe the control levels in terms of the control elements introduced.

The NPD project model elements are grouped into:

4.1 General constraints:
- a fixed development budget for the NPD project
- a fixed deadline for the NPD project: (Oorschot, 2001; Repenning 2000; Eisenhardt, Tabrizi 1995)
- a set of current customer needs with their corresponding normalized importance weights (i.e. the weights sum up to one)
The importance weights can be found using the Analytical Hierarchy Process or a similar procedure (Kusiak 1995).

- *a set of current product specifications with their:

  - *ideal and minimal target values for their corresponding metrics* (Askin, Dawson 2000; Ulrich, Eppinger 2000)
  - *relative importance rating*

As in Ulrich, Eppinger (2000), the working assumption is that a translation from customer needs to a set of measurable product specifications is possible and that meeting specifications will therefore lead to satisfaction of the associated customer needs. Each specification consists of a *metric* and a *value* (i.e. a number, range, or inequality). The product specification setting starts with a list of metrics and their relative importance, which are refined and flown down to the lowest level of the WBS structure (Ulrich, Eppinger 2000). The initial metrics should be complete, practical, in general dependent variables. After their flow-down via the specification tree we set the ones from the lowest level of the tree as the current product specifications.

The process of setting the metrics ideal target values is generally a subjective and heuristic one. However, mathematical models are also available (Askin, Dawson, 2000).

The importance rating of a metric is derived from the weights of the customer needs it reflects. Ulrich, Eppinger (2000) do not recommend a formal algorithm, but for the case of few important specifications, conjoint analysis can be a solution. If the level of detail of the product specifications supports the assumption of independent metrics their relative importances can be obtained via regression analysis (Askin, Dawson, 2000; Yoder, Mason, 1995).

### 4.2 The set of system states:

The state of the system at the beginning of each review period is a *directed acyclic graph of design tasks*. Similarly to Sieger et al. (2000), we choose the set of states of the system without abandoning the proven benefits provided by network analysis in the management of projects.

Ideally, a decision making moment should occur whenever a design task starts, a new design task or a new activity arrives changing the known information about the project. To avoid the discretisation of the project duration into very small units, one can decompose the project into stages (review in Tavares, 2002). We construct stages for our graph, by associating a representation into independent sets to it: sets of unordered design tasks (no precedence relations between any two of them) and all having the same length of the longest path from the start dummy node to them (in the precedence graph) (see Figure 4.).

Figure 4.

Thus, the concept of a *T*-stage network naturally associates the *t*-th decision moment with the allocation of design tasks from the *t*-th set of the partition
of nodes. Also, empty sets can be added to achieve equidistancy of the control points, or if the controller wants to control more often than the number of independents sets. The partition of the set of nodes gives the sets of design tasks that can be allocated at the beginning of a review period. All the design tasks allocated in the same review period can be performed in parallel.

For controlling coupled (interdependent) tasks, the Design Structure Matrix (DSM) was developed as an alternative for formal project-scheduling representations (Eppinger et al., 1994; Krishnan, Ulrich 2001). If the DSM can be organized into a lower triangular form, the coupling is eliminated. Otherwise, if one would collapse the diagonal blocks for reducing the DSM matrix to a precedence network, the essential information on the design iteration within blocks would be lost. However, DSMs require a complete information on the number of design tasks, and their relationships, assumptions not suitable in the case of a NPD with a high technological uncertainty. Our state representation tries to capture the coupling information, while not giving up to the technological uncertainty modelling. In the beginning of the NPD project we start with a DSM representation, we collapse each remained block on its diagonal into one design task, and we model the task in detail, up to all its constituting activities. Thus, we construct a network of design tasks, which is however stable for only one review period. At its end, the structure of each design task is updated, and so we keep track of most of the changes that occurred into the former blocks, including a possible resequencing of the block elements.

4.3 The performance, cost and market-payoff structure:

The performance and valuation control concepts are to the best of our knowledge new. They follow from the assumption of the one-to-one mapping between the current product specifications and the design tasks, justified earlier.

Each design task has

- a number of increasing performance levels giving the quality of its execution. They are induced by a scaling in between the minimal and the ideal target values for the corresponding current product specification metric. Each performance level consists of a list of planned activities (to be sequentially performed (Aslaksen, Belcher, 1992)) with solving times random variables independent identically exponentially distributed (see for empirical evidence Best, 1995; Reed, 1998). To attain a performance level, we assume that the engineer has to sequentially execute the design task at all previous performance levels, which implies different stochastic durations for the solving time, depending on the level initially specified. The split of each level into activities gives a uniform measure of the difficulty implied by its realization. For each design task a minimal performance level has to be achieved.
a cost function gives the incremental change in cost associated with performing one more planned activity, of one of its performance levels. This function models all non-engineer capacity related costs.

a time dependent contribution function. A time dependent value gives the maximal contribution of each design task \( k \), in achieving each customer need. Its time dependent contribution function is obtained by scaling its corresponding maximal contribution at that time instant, for its performance levels.

At the beginning of a review period \( t_0 \), we obtain the design tasks maximal contribution values as follows. Without loss of generality we consider the specification tree in Figure 5, and its corresponding Quality Function Deployment (QFD) waterfall chart in Figure 6.

The \( w_\delta (t_0) \), \( \delta \in \{ 1, ..., \Delta \} \) represent the normalized weights (i.e. \( \sum_{\delta=1}^{\Delta} w_\delta (t_0) = 1 \)) corresponding to the current customer needs. The first QFD chart contains the normalized quantifiers, \( \alpha_{ij} (t_0) \), \( \delta \in \{ 1, ..., \Delta \} \), \( j \in \{ 1, ..., p \} \), for the contribution of the maximal target value for the metric corresponding to the system specification \( j \), in achieving the customer need \( \delta \). The second one contains the normalized quantifiers, \( \beta_{jk} (t_0) \), \( j \in \{ 1, ..., p \} \), \( k \in \{ 1, ..., r \} \), for the contribution of the maximal target value for the metric corresponding to the subsystem specification \( k \), in achieving the maximal target value for the metric corresponding to the system specification \( j \).

A normalized quantifier for the contribution of the maximal target value for the metric corresponding to the subsystem specification \( k \) (i.e. design task \( k \)), in achieving the customer need \( \delta \) is given by \( \sum_{j=1}^{p} \beta_{jk} (t_0) \alpha_{\delta j} (t_0) \) since the maximal contribution of the design task \( k \) at \( t_0 \) is \( \sum_{j=1}^{p} \sum_{\delta=1}^{\Delta} \beta_{jk} (t_0) \alpha_{\delta j} (t_0) w_\delta (t_0) = \sum_{\delta=1}^{\Delta} \sum_{j=1}^{p} \beta_{jk} (t_0) \alpha_{\delta j} (t_0) w_\delta (t_0) \). It cumulates the contributions of the maximal target value for its corresponding metric in achieving the maximal target values for the metrics corresponding to the system specifications.

Also, a more detailed QFD chart relates directly the customer needs with design tasks specifications, and consequently to the realization of each design task up to its maximal performance level (see Figure 7.) via \( \sum_{j=1}^{p} \beta_{jk} (t_0) \alpha_{\delta j} (t_0) \), \( \delta \in \{ 1, ..., \Delta \} \) quantifiers.

The project has a market payoff structure:
Design task contribution functions are useful for maximizing the customer satisfaction subject to technological and cost constraints. For each customer need, we construct a time dependent cumulative contribution function of the performance levels of the design tasks belonging to it in the flow-down specification process. We obtain it by cumulating the design tasks contributions given in the customer needs/design tasks QFD chart (as in Fig. 7), and using their scaling procedure for the different performance levels.

There are different levels of customer’s satisfaction for the achieved new product, function of the distance between the cumulated and the ideal value for each of the customer’s needs. An S-curve type of market payoff function gives an expected market value for each cumulated value of a customer need achieved at the deadline. Different types of S-curve models and analytical cumulative market payoff functions (general: Yoshimura, 1996; Huchzermeier, Loch 2001; linear: Askin, Dawson, 2000) are encountered in literature. The last ones describe the market value of how well a new product fulfills several customer needs.

We may derive for detailed planning level optimization purposes design task market payoff functions, which should coincide with the design task contribution functions, for linear models.

4.4 The technological uncertainties:

- a time dependent arrival rate of new activities: according to a Poisson process, during a review period new activities arrive to the design tasks in progress. They appear as a result of the incapacity of solving the design task with its current description, so we model them to have preemptive resume priority over the planned activities. In later stages, the time dependent arrival rate decreases.

- a time dependent arrival rate of new design tasks: the integration of the knowledge created by the interaction in between the three considered NPD phases into a coherent product definition may add/delete design tasks from the project structure (Tatikonda, Rosenthal, 2000a, b; Oorschot, 2001) Their deletion is modeled by allowing the controller to set their desired performance level to zero, if the current minimal performance level is zero. While, their addition is modeled by assuming general Markovian review period-dependent arrival processes of new design tasks. Each process consists of design tasks concurrent either with design tasks to be allocated to the team at the beginning of the current review period, or with those allocated in previous NPD project review periods. Their arrival rate decreases in time. The new design tasks arrived during one review period are assumed to have a common performance level structure, and an identical value function. They are associated to customer’s need transformation into product specifications at the beginning of the next review period.
4.5 The state updating information (given at the end of each review period):

- for each already allocated design task, the performance level already achieved, and, per level, the number of remaining planned activities;

- for the sequences of newly arrived design tasks: their cardinality, their common number of activities per performance level, their common value function.

Given the previous definitions of the model elements, let us look at the control model we propose. The scheme of the control structure is given in figures 8. and 9. and has a total number $T$ of review periods. Review period $t$ starts at time instant $t$ and ends at time instant $t + 1$.

Figure 8.

Figure 9.

At the aggregate decision level the performance levels of the design tasks are set, while at the detailed planning level a nonpreemptive schedule is, generally, obtained for a relatively short planning horizon, e.g. two review periods. After updating the design task network structure, the project management may decide to decrease/increase the performance levels of some of the already scheduled design tasks, but not finished yet, due to the addition/deletion of design tasks and the limited capacity available versus their stochastic solving time. Then the design tasks and/or the number of their planned activities is changed. Since a feasible schedule is obtained by means of stochastic ordering re-scheduling may occur.

5 Conclusions

We have presented a hierarchical framework for the control of the NPD project detailed design phase under hard time constraints. The framework takes into account both the market uncertainty regarding the customer needs and the technological uncertainty regarding the product specifications realizability. The project is periodically controlled: first the design tasks structure is updated; afterwards we set their required performance levels, and we allocate design tasks to engineers in order to maximize the expected market value that can be delivered with a certain probability at the deadline. We combine research results in the fields of new product management, systems engineering, project planning and control, human performance management, and production scheduling. This produces an exhaustive list of concepts, variables and relationships that enable us to formerly describe the hierarchical control system. In particular, we modelled:

- the uncertainty regarding the structure of the project, and the capacity needed per design task
the relationship between the design task’s quality (expressed in performance levels) and the expected market value of the new product

The defined model elements are rich enough to incorporate the available knowledge from the relevant fields such as new product management and systems engineering, and still allow at each control level for the mathematical analysis of the process. In a subsequent paper we present the mathematical formulation of the hierarchical control framework, and discuss new or already available operations research methods and techniques that can be used for the project analysis and for solving the detailed and aggregate decision level problems.

References:


Figure 1: Phases of a flexible NPD process

Figure 2: Specification tree after the flow-down of product specifications, Aslak- sen, Belcher, (1992)

Figure 3: NPD process and resource structure

Figure 4: NPD control model

Figure 5: Aggregate decision at the beginning of review period \( t_0 : (t_0, t_0 + 1] \)

Figure 6: Stages of the directed acyclic graph describing the state of the system at time instant \( t_0 \)

Figure 7: A particular specification tree

Figure 8: QFD waterfall for the above specification tree

Figure 9: Customer needs/design tasks QFD chart
Figure 1:
Documentation required for implementation phase to develop the "design task"

Figure 2:
Network of design tasks to be performed by a NPD team in a short time planning horizon

Sequence of design tasks to be performed by an engineer in a short time planning horizon

Figure 3:
Review period $t_0: (t_0-1, t_0]$ Review period $t_0+1: (t_0, t_0+1]$  

- Market/customer information  
- Cumulative market payoff function  
- Updated network of design tasks $RN(t_0)$ (with precedence constraints)  
- Deadline  
- Minimal ambition level  
- Current safety margins  
- The exponential rate of solving any activity of a design task  
- Updated network of design tasks at time $t_0$  
- Technologically updated network of design tasks at time $t_0$ (with precedence constraints)  
- The set of design tasks to be allocated at $t_0$  
- Updated structure of design tasks which are already available at the detailed planning level  
- The performance levels of available design tasks at $t_0$  
- Short time planning horizon  
- The sequence of design tasks for each engineer, for their short time planning horizon  

Engineering process state at time $t_0$  

Engineering process state at time $t_0+1$  

The state updating information for review period $t_0+1$  

Figure 4:
The state updating information
(the network of design tasks,
the available team capacity)
after time $t_0$

- current safety margins
  for achieving the new product
- minimal performance levels
  of design tasks
- deadline
- cumulative market payoff function
- the exponential rate of solving any activity of a design task
- NPD budget

Figure 5:
Figure 6:
Figure 7:

- customer needs

- the time dependent decomposition into system specifications

- the time dependent decomposition into subsystem specifications

- describing design tasks

- work content

- the time dependent values of the design tasks maximal contributions
\[ \Theta(k, t_0) = \sum_j \beta_j(k, t_0) \sum_\delta \alpha_{\delta j}(t_0) w_\delta(t_0) \]
\[
\sum_{\delta} \left( \sum_{j} \beta_{jk}(t_0) \alpha_{\delta j}(t_0) \right) w_\delta(t_0)
\]

Figure 9: