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Managing NPD: Cost and Schedule Performance in Design and Manufacturing

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In this field study, conducted at a leading avionics guidance systems manufacturer, we gathered primary data on time and cost performance of both the design and manufacturing phases of new product development (NPD). We modeled the impact of the management levers relating to oversight, the intensity of design specialization, and the level of interaction with the customer. The study highlights the necessity of leveraging the interdependencies between the design and manufacturing phases in NPD.

Key words: time to market; new product development; project management; cost and time trade-offs; customer involvement; financial metrics; NPD
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1. Introduction

New product development (NPD) allows firms to evolve with their marketing and technical environments (Brown and Eisenhardt 1995, Clark and Fujimoto 1991). Several articles in the academic literature (Brown and Eisenhardt 1995, Cohen et al. 2000, Eppinger 2001, Krishnan and Ulrich 2001, Lee et al. 2000, Novak and Eppinger 2001), as well as the popular press (e.g., *Business Week* 1992) have focused on various methods for effective NPD. It is widely accepted in both the marketing literature (e.g., Urban and Hauser 1993) and the operations literature (e.g., Hayes et al. 1988) that NPD can be considered to take place in multiple steps. In this field study, we consider the entire NPD process to comprise two phases: *design* and *manufacturing* (Pahl and Beitz 1988).

The design phase potentially impacts downstream manufacturing and has been postulated to affect both the *cost* and *lead time*. In the operations literature (Desai et al. 2001, Fisher 1997) it has been pointed out that appropriate investments in design lower unit cost. Several studies have suggested that activities in the design phase often determine approximately 80% of manufacturing cost (Miller 1988, Ullman 1992). Ulrich and Pearson (1998) state "Because the design activity specifies the materials, part production processes and assembly requirements of a product, product design is one of the determining factors of manufacturing cost." Several works have also suggested that design can potentially affect the manufacturing and assembly lead times downstream, with extensive literature on design for assembly (DFA) or design for manufacturing (DFM) (Coleman 1988, Miller 1988, Ulrich et al. 1993, Eppinger et al. 1990). Our study is unique in that it looks at the lead times and cost of *both* the design and manufacturing phases, and treats each one as a *separate* dependent variable, affected by managerial levers in the design phase

Past studies have also focused on the effects of different aspects of design. One body of work in the production literature (Ulrich et al. 1993, Ulrich and Pearson 1998) looks at the *content* of the design (e.g., the number of parts, the complexity of each part), while another body of work, in both the marketing and production literatures, looks at the *management* of the design process (e.g., Allen 1971, 1977; Ancona and Caldwell 1992; Griffin and Hauser 1992; Ha and Porteus 1995). In this study, we focus on the *management* of the design process. Earlier work has examined factors such as the cross-functional nature of the NPD team, the external and internal communications of the team, the political power of the project manager, and the degree of customer and supplier involvement. Good discussions can be found in Brown and Eisenhardt (1995) and Krishnan and Ulrich (2001). We focus on three drivers related to the management of the design phase of NPD: (i) the degree of *specialization input* in design, (ii) the degree of *oversight* by the project manager in the design phase, and (iii) the intensity of *customer interaction* during design. Next, we position each of these managerial levers in the context of earlier work.

(i) Specialization. Specialization captures the degree of involvement of specialists during the design phase. This notion of specialization should be distinguished from the idea of cross-functionality in the design process. The latter has been shown to be beneficial in both the marketing literature (Carmel 1995, Griffin 1997, Gupta and Wilemon 1990, Mabert et al. 1992, Moenart and Souder 1996, Rochford and Rudeluis 1992) and earlier work in the operations area (Krishnan et al. 1997, Ulrich and Ellison 1999). Specialization, in our context, is *complementary* to cross-functionality. It indicates representation *within the function*, while cross-functionality is representation across various functions. Specifically, with regard to the design phase, cross-functionality refers to the extent of input from nondesign personnel in the design phase. In contrast, specialization refers to the degree of input from experts in specialized subfunctions within design. At our research site, the degree of specialization during design varied significantly across projects, whereas the degree of cross-functionality was similar.

Increased specialization could be argued to be either adverse or beneficial. On the negative side, first, specialist designers are scarce resources and tend to work on multiple projects concurrently, leading to issues of congestion (Adler et al. 1995). Second, specialist design hours carry premium billing rates. Third, the increased intensity of specialization in design leads to a subsystem focus, rather than a system focus. This necessitates increased coordination across specialists to achieve superior system performance. On the positive side, first, specialists are better able to steer the design of subsystems to match customer requirements. Second, specialist designers can better deploy design for manufacturing concepts within their own area of influence, thereby enhancing downstream manufacturing performance. Third, as stated in Nobeoka (1995) and Nobeoka and Cusamano (1997), specialists can leverage their experience across multiple projects. Our analysis highlights the magnitude and the nature of such trade-offs from varying specialization in design-intensive environments.

(ii) Oversight. The second factor we study is the degree of oversight by the project manager in the design phase. The effects of oversight in NPD projects are still not well understood. This lack of research is recognized by Brown and Eisenhardt (1995), who state "Surprisingly, however, there is very little research about appropriate internal *management* skill for project leaders…." Eisenhardt and Tabrizi (1995) show that more frequent milestones and frequent iterations of product design (implying greater oversight) are better for the design of products that are immature and where there is uncertainty in the design process, while a more structured approach is appropriate for the design of mature products like automobiles. In the latter case, there is less uncertainty in design. In the production literature, Ha and Porteus (1995) point out the trade-offs between too much oversight (increased lead times) and too little oversight (not enough communication between team members and poorer quality designs). In their survey of past NPD work, Krishnan and Ulrich (2001) state "practitioners seem to struggle to strike the right balance between excessive intervention and inadequate oversight."

The dichotomy on the efficacy of different managerial process controls in NPD further adds to this lack of understanding. Process controls occur when managers specify the means used to achieve goals and monitor the activities pursued. On one hand, empirical work (e.g., Cooper 1993, Wheelwright and Clark 1992) suggests that NPD success is affected positively by process management. In the production literature, specific process-management methodologies such as the phase-gate process (Cooper 1993), the quality function deployment method (Hauser and Clausing 1988), and the design structure matrix (DSM) (Eppinger et al. 1990, Eppinger 2001, Steward 1981), have been praised in both the academic and popular presses (Bonner et al. 1998). On the other hand, earlier work by Ouchi (1979), Ouchi and Maguire (1975), and more recent work by Jaworski et al. (1993) suggest that heavy reliance on formal process controls is counterproductive for NPD. For example, Bonner et al. (1998) find that greater team autonomy positively affects the schedule and cost of NPD. In this study, we contribute to this literature in both the marketing and operations areas by studying the opposing influences of managerial oversight in the design phase of NPD.

(iii) Intensity of Customer Interaction. The third factor we study is the effect of customer interaction on performance metrics and its interaction with the two managerial levers described earlier: specialization and oversight. While the interaction of the NPD teams with external members of the organization (outside the team), has been well studied (Brown and Eisenhardt 1995), the effect of user (customer) interaction in the design phase has received less attention. There is growing recognition in the literature that customer interaction leads to shorter lead times (Cooper 1995, Gupta and Souder 1998, Thomke and von Hippel 2002). As discussed in Thomke and Nimgade (2000), "Designers often seek perfection which could potentially lead to cost and time overruns—also known as *creeping elegance*." Increased customer interaction mitigates this creep. Constant communication with the customer also leads to less design rework, leading to better financial and time performance in the design phase. There is, however, a paucity of research on the *interaction* of the degree of customer interaction with the other management drivers, such as the degree of oversight and the intensity of specialization during design. In this work, we attempt to quantify these interactions. In the next section we describe the research site and data collection, and frame the key hypotheses.

2. Research Site and Hypotheses

The unit of analysis for our study is the individual NPD project at Missile Systems, Inc.,[1] a leading designer and manufacturer of advanced missile guidance systems. Their customer base represents leading companies in the aerospace industry in the United States (e.g., Lockheed Martin and Boeing), as well as defense departments of foreign governments. The design of the guidance systems is highly customized and involves the simulation of flight guidance of missiles, with precise monitoring of critical parameters such as vibration, temperature, and rotational and linear speeds. Subsequent to the award of a contract at Missile Systems, Inc., project managers make several choices. They determine the mix of generalist and specialist designers. The latter have very specialized skills in areas such as strength of materials, materials fracture, thermal effects, electronic hardware, and control circuits. Several of the design tasks can be accomplished by either generalists or specialists. A second decision is the level of managerial supervision in the design phase. Some project managers prefer to finely decompose the tasks in the phase, whereas others tend to limit their oversight. A third choice is the level of customer interaction. Some project managers favor a higher level of sign-offs and communications with the customer compared to others. Next, we describe our data collection efforts at Missile Systems, Inc.

Project data at Missile Systems, Inc., were collected for 53 distinct projects completed during 1993–2001 the period. For each project, we interviewed personnel from marketing, design, engineering, manufacturing, and accounting, and collected project-specific data to capture the resources planned and expended during both the design and manufacturing phases. Wherever possible, triangulation was performed to confirm the accuracy of the data. Eleven projects were dropped because of missing data. Statistical checks were performed to ensure that no bias had resulted. The average project size was \$220,000, and the average project duration was approximately three years.

2.1. Operationalization of Variables

Specialization in design represents the intensity of deployment of specialists during the design phase. This can be captured along two dimensions: (a) the percentage of design resources allocated to specialist designers versus generalist designers, and (b) the number of specialties. The first dimension captures the "aggregate" intensity of specialization during design and the second accounts for the "diversity" of skills deployed. Given the sensitive nature of the defense projects in this field study, details for (b) were restricted, and were made available only for a representative sample of projects. Analysis of this sample of projects revealed a high correlation of 0.87 between (a) and (b). This high correlation implies that whenever specialists are brought in, irrespective of their specialty, they are engaged for similar percentages of the design budget. Therefore, we use (a) to jointly capture both the dimensions of specialization, and operationalize it as follows

$$\mathrm{SP} = \frac{(\text{Budget for specialist designers})}{(\text{Total design budget})} \times 100.$$

In our data set, the variation in SP was 4% to 95%.

The second independent variable in our study is *oversight*. Managerial oversight is the degree of managerial control that is exercised by the project manager for a particular project. At Missile Systems, Inc. (as in most organizations), the project managers monitored each project by tracking specific tasks performed by the design team. To compare the intensity of project monitoring meaningfully across projects, we normalized the number of tasks monitored in the design phase by the overall design budget for that project. Hence, oversight is defined as

$$\mathrm{OV} = \frac{(\text{Number of tasks monitored in the design phase})}{(\text{Total design budget})}.$$

In our data set, the range in OV across projects was 0.06 to 3.51.

The third driver of performance is the intensity of *customer interaction* during the design phase. Project managers confirmed that higher design budgets necessitated a proportionately higher number of customer sign-offs. After controlling for the design budget, the projects in our data set showed a wide variation in the intensity of customer sign-offs in the design phase. Therefore, we operationalize the degree of customer interaction to be

$$\mathrm{CUSTINT} = \frac{(\text{Number of customer sign-offs in design phase})}{(\text{Total design budget})}.$$

In our data set, the range in CUSTINT was 0.28 to 3.48.

We also create two interaction variables that capture the interaction between intensity of customer interaction and the other two independent variables (specialization and oversight). These interaction variables

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[1] The name of the company has been disguised because of confidentiality restrictions in defense contracts.

are defined as the products of the respective pair of variables, as shown below:

$$\text{SP-CUSTINT} = \text{SP} \cdot \text{CUSTINT},$$

$$\text{OV-CUSTINT} = \text{OV} \cdot \text{CUSTINT}.$$

Next we discuss the dependent metrics for the study. For each project, we tracked the time and financial performance of each phase as dependent variables. The time performance is measured by the timeliness of the completion of each phase, with positive numbers indicating completion of that phase ahead of schedule. Interproject comparison is accomplished by normalizing by the budgeted time in each phase. We therefore define the following time performance metrics for the design and manufacturing phases, respectively:

$$\text{DES-SCHED} = \frac{(\text{Time ahead of schedule for the design phase})}{(\text{Time budgeted for the design phase})} \times 100$$

$$\text{MFG-SCHED} = \frac{(\text{Time ahead of schedule for the manufacturing phase})}{(\text{Time budgeted for the manufacturing phase})} \times 100.$$

Likewise, for the parallel financial metrics defined below, positive numbers indicate lower expenditures relative to allocations, resulting in savings in that phase:

$$\text{DES-SVNGS} = \frac{(\text{Cost savings in the design phase})}{(\text{Total design budget})} \times 100$$

$$\text{MFG-SVNGS} = \frac{(\text{Cost savings in the manufacturing phase})}{(\text{Total manufacturing budget})} \times 100.$$

2.2. Hypotheses

In our model, we have four dependent variables (DES-SCHED, DES-SVNGS, MFG-SCHED, MFG-SVNGS), shown later in the columns of Table 1, and three independent variables (OV, SP, CUSTINT) and two interaction variables (OV-CUSTINT, SP-CUSTINT) shown as rows in Table 1. In addition, there are two instrumental variables[2] (est. DES-SCHED and est. DES-SVNGS). Next we postulate the key hypotheses of the associations between these sets of variables. The numbering of the hypotheses indicates the pair (dependent variable, independent variable). For instance, Hypothesis 3b refers to the association between the third-column variable (MFG-SCHED) and the second-row variable (SP) in Table 1.

Table 1 Summary of Hypotheses' Directions of Influence

	I DES-SCHED	II DES-SAVNGS	III MFG-SCHED	IV MFG-SAVNGS
(a) OV	−	−	+	+
(b) SP	+	−	−	−
(c) CUSTINT	−	−		
(d) OV-CUSTINT	+	+		
(e) SP-CUSTINT	+	+		
(f) DES-SCHED			−	
(g) DES-SVNGS				−

Our first set of hypotheses (1a, 1b, 1c, 1d) pertain to the first dependent variable: DES-SCHED. It measures the conformance to the schedule in the design phase. Because design is a creative process (Adler et al. 1995), more oversight results in a more detailed consideration of downstream manufacturing concerns, as well as non-design-related activities such as presentation preparation, meetings, and reviews (Ha and Porteus 1995). On the other hand, Ha and Porteus (1995) and Brown and Eisenhardt (1995) also emphasize that more oversight would lead to better control. Managers have thus expressed opposing opinions pertaining to the direction of influence of OV. Given the high level of design complexity for the products in our study, we test the hypothesis of a negative influence of OV on DES-SCHED.

Hypothesis 1a. *Higher values of OV will lead to lower values of DES-SCHED.*

Increased specialization could be beneficial or adverse to time performance. While having a higher specialization is potentially useful for complex design processes, negative impacts can occur. For instance, with higher specialization, designers work on multiple projects concurrently, leading to issues of congestion (Adler et al. 1995). On the contrary, specialists can leverage their prior experiences in their area of functional expertise and hence complete the design task in a more timely manner (Nobeoka 1995, Nobeoka and Cusamano 1997). Because the design process in this study is highly complex, we hypothesize that a higher intensity of specialization in design should have payoff in terms of faster execution of the design phase, offsetting the potential negative impact due to congestion effects.

Hypothesis 1b. *Higher values of SP will lead to higher values of DES-SCHED.*

Next, we capture the effect of the intensity of customer interaction (CUSTINT) on the design schedule. Listening to the customer, on one hand, requires

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[2] The reason for the use of this instrumental variable is explained later in this section and in §3, where we discuss the structural form of the system of equations.

substantial time commitment, leading to engineering changes and delays during the design phase. Schedules are likely to slip; this is captured in Hypothesis 1c, which stipulates an adverse impact on the design schedule with high intensities of customer interaction.

Hypothesis 1c. *Higher values of CUSTINT will lead to lower values of DES-SCHED.*

On the other hand, the organization can leverage input from the customer with the right amount of customer interaction. Project managers can utilize sign-offs with the customer to coordinate across subsystem design. Iansiti (1998) has emphasized this role of project managers as *T* experts, who have both adequate depth of knowledge and the breadth to reduce system-level design rework. The specialists can also use the customer sign-offs to better understand the requirements of the customer (Cooper 1995, Gupta and Souder 1998). A better understanding of requirements by specialists leads to less design rework, and faster completion of approved designs. Thus, management levers such as oversight interact with intensity of customer sign-offs. We model this through the interaction variables OV-CUSTINT and SP-CUSTINT. This leads to the following two hypotheses:

Hypothesis 1d. *OV-CUSTINT (the variable representing interaction between OV and customer interaction) will have a positive influence on DES-SCHED.*

Hypothesis 1e. *SP-CUSTINT will have a positive influence on DES-SCHED.*

Next, we examine the second dependent variable: DES-SVNGS, shown in Column 2 of Table 1. This outcome variable represents the dollar savings during the design phase. While the overall financial performance of a project has been considered in the past (e.g., Ulrich et al. 1993, Ulrich and Pearson 1998), our field study is the first work that systematically examines the financial performance of the design phase explicitly. In the case of products with complex designs (as in our study), the design phase consumes a significant percentage of the overall time and money. We consider DES-SVNGS separately from DES-SCHED, as our interviews with senior management at Missile Systems, Inc. revealed that faster completion of the design phase may or may not lead to net dollar savings. The hypothesized effects of OV, CUSTINT, and the interaction variables OV-CUSTINT and SP-CUSTINT on DES-SVNGS are similar to the effects on DES-SCHED (Hypotheses 2a, 2c, 2d, and 2e in Table 1). However, the direction of influence in Hypothesis 2b differs from its counterpart Hypothesis 1b, as explained next.

In contrast to the posited favorable impact of SP on DES-SCHED (1b), the effect on DES-SVNGS involves trade-offs. Managers can achieve faster completion of design tasks with specialization, but at the cost of higher outlays in the design phase. Specialized designers tend to command premium salaries. Hence, the direction of the impact of added specialization in the design phase can go either way. We hypothesize that while higher SP leads to time savings, it is achieved by more dollar outlays, and hence the net effect of SP on design savings should be adverse. Hypothesis 2b asserts this adverse impact of SP below.

Hypothesis 2b. *Higher values of SP will lead to lower values of DES-SVNGS.*

The third dependent variable in our analysis is MFG-SCHED (shown in Column 3 of Table 1). It measures the conformance to the schedule in the manufacturing phase from a project-management standpoint. Unlike in the design phase, higher OV is desirable from an assembly coordination standpoint. A greater degree of managerial oversight in the design phase would lead to better coordination amongst the designers, and hence easier assembly of the different components in the manufacturing phase. The complex nature of the products in the study amplifies the assembly problems that would result. Thus, we expect a net positive impact of OV on MFG-SCHED, as shown in Hypothesis 3a below:

Hypothesis 3a. *Higher levels of OV lead to higher values of MFG-SCHED.*

In contrast, higher SP entails components being designed by different personnel, which can potentially lead to downstream assembly problems in manufacturing. Quality hold-ups in manufacturing can also occur if tests reveal shortcomings in system performance. Thus, while higher SP is desirable from a design schedule standpoint (Hypothesis 1b), we hypothesize that lower SP is desirable from an assembly and testing standpoint:

Hypothesis 3b. *Higher amounts of SP lead to lower amounts of MFG-SCHED.*

A widely accepted view in the design for manufacturing (DFM) literature is that up-front investment in design pays off in the subsequent manufacturing phase, both in terms of time and money. This implies that more investments in design time, *if* channeled to the right DFM activities, will have payoffs subsequently in manufacturing schedules. If investments in design time are spent on ineffective activities from a manufacturing viewpoint, then downstream schedules could potentially be adversely affected. We posit the former effect, that manufacturing schedules are improved with greater time investments in design:

Hypothesis 3f. *Lower values of DES-SCHED are associated with higher values of MFG-SCHED.*

Referring to Hypotheses 3a and 3f, note that we separate the effects of OV on MFG-SCHED into two components. The first is the net effect of OV on DES-SCHED, which in turn affects the MFG-SCHED. This is the ripple or indirect effect of OV on MFG-SCHED (note that DES-SCHED is affected by several variables besides OV). The second is the direct effect of OV on MFG-SCHED (independent of its ripple effect, which was mediated by the DES-SCHED). A similar argument applies to SP (Hypotheses 3b and 3f).

Finally, we consider the effects of the drivers on the fourth dependent variable: MFG-SVNGS (Column 4 of Table 1). We posit similar directional impacts of OV, SP, and DES-SVNGS on MFG-SVNGS. For brevity, we do not discuss the related hypotheses.

3. Model

We propose the following system of equations to analyze the data. The model specification is based on the hypotheses development discussed earlier, in §2.2.

$$\begin{aligned}\text{DES-SCHED} &= \alpha_1 + \beta_{11}\text{OV} + \beta_{12}\text{SP} + \beta_{13}\text{CUSTINT}\\ &\quad + \beta_{14}\text{OV-CUSTINT} + \beta_{15}\text{SP-CUSTINT} + \varepsilon_1 \end{aligned} \tag{1}$$

$$\begin{aligned}\text{DES-SVNGS} &= \alpha_2 + \beta_{21}\text{OV} + \beta_{22}\text{SP} + \beta_{23}\text{CUSTINT}\\ &\quad + \beta_{24}\text{OV-CUSTINT} + \beta_{25}\text{SP-CUSTINT} + \varepsilon_2 \end{aligned} \tag{2}$$

$$\text{MFG-SCHED} = \alpha_3 + \beta_{31}\text{OV} + \beta_{32}\text{SP} + \beta_{33}\text{DES-SCHED} + \varepsilon_3 \tag{3}$$

$$\text{MFG-SVNGS} = \alpha_4 + \beta_{41}\text{OV} + \beta_{42}\text{SP} + \beta_{43}\text{DES-SVNGS} + \varepsilon_4. \tag{4}$$

Note that Equations (1) and (3) are related, as are Equations (2) and (4). Thus, our structural model essentially consists of two sets of recursive equations, with one set modeling the linkages between the time metrics of the two phases, and the second set modeling the interdependencies of the financial metrics between the two phases.[3] We can estimate Equation (1) by the Ordinary Least Squares (OLS) method and use the predicted values of the dependent variable DES-SCHED in Equation (3) and estimate the resulting equation.[4] Likewise, the second set of equations linking DES-SVNGS to MFG-SVNGS can be estimated. Table 2 shows the estimated coefficients of the model. The values in parentheses are t-statistics.

Although the model has two sets of recursive equations, we can allow for the residuals of the equations in each set to be correlated, and estimate the parameters allowing for such a correlation.[5] We can also allow for the residuals to be correlated across *all* the equations (in a seemingly unrelated sense), but because of the large sample size required for such a procedure, we refrain from such specifications and prefer parsimony.

First, we discuss the estimates for the design phase (Equations (1) and (2)). As hypothesized, DES-SCHED is negatively affected by OV (Hypothesis 1a, $\beta_{11} = -9.38$), and CUSTINT (Hypothesis 1c, $\beta_{13} = -15.25$). As expected, SP is seen to have a positive impact on DES-SCHED ($\beta_{12} = 6.62$, Hypothesis 1b). Furthermore, the interaction terms of OV-CUSTINT and SP-CUSTINT both impact the DES-SCHED favorably ($\beta_{14} = 5.38$, $\beta_{15} = 6.26$). Thus, Hypotheses 1a–e are all supported by the estimated model. The data, however, support some of the hypotheses for Equation (2) (for the dependent variable DES-SVNGS). We find strong support for Hypothesis 2a ($\beta_{21} = -160.99$), implying that higher levels of OV lead to lower savings. We find support for the contra of Hypothesis 2b ($\beta_{22} = 342.2$), implying that higher levels of specialization generate more savings in the design phase. We did not find support for Hypotheses 2c, 2d, and 2e, indicating no evidence that CUSTINT, OV-CUSTINT, and SP-CUSTINT impact the financial performance in the design phase.

Next, we move to the equations for the manufacturing phase. The results for Equation (3) (for the dependent variable MFG-SCHED) show lack of support for Hypotheses 3a and 3b, implying no empirical evidence to support the hypothesized direct effects of OV and SP on MFG-SCHED. However, there is significant support for Hypothesis 3f ($\beta_{35} = -16.7$), implying that upstream time investments (slippage in design phase) translate to downstream time savings in the manufacturing phase. Conventional project scheduling would suggest that a slippage in design would result in further delaying downstream activities. The negative sign of β_{35} implies just the opposite. The magnitude also suggests that downstream gains are amplified.[6]

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[3] There could potentially be two-way interdependencies between time and cost in each phase of NPD. However, simultaneity is not an issue in this case. This was confirmed on estimating the simultaneous model where the parameters were found to be insignificant. It could be attributed to the complex sequence of project activities where higher cost does not necessarily lead to faster project completion, unless the activity is on the critical path. Further, the stochastic nature of the project network makes it difficult to determine the critical activities.

[4] See Theil (1971) and Judge et al. (1985) for a discussion of the 2SLS analysis performed here.

[5] In this case, we checked the rank and order conditions (Theil 1971).

[6] The time impact on manufacturing for a unit slippage in design = β_{35} · time budgeted for manufacturing/time budgeted for design.

Table 2 **Estimated Coefficients of the Model**

Variables	DES-SCHED Equation (1)	DES-SVNGS Equation (2)	MFG-SCHED Equation (3)	MFG-SVNGS Equation (4)
INTERCEPT	13.88 (2.66)*	52.79 (0.29)+	112.58 (2.28)	39.65 (3.75)
OV	−9.38 (−5.48)	−160.99 (−2.66)	−2.2 (−0.14)+	13.53 (1.69)
SP	6.62 (1.85)	342.2 (2.72)	74.4 (1.38)+	−26.45 (−2.00)
CUSTINT	−15.25 (−4.46)	−5.19 (−0.04)+	NA	NA
OV-CUSTINT	5.38 (5.32)	−37.17 (−1.04)+	NA	NA
SP-CUSTINT	6.26 (2.29)	−63.30 (−0.65)+	NA	NA
DES-SCHED (instrumental)	NA	NA	−16.7 (−5.24)	NA
DES-SVNGS (instrumental)	NA	NA	NA	−7.84 (−2.45)

Note. *Values in parentheses are *t*-statistics. +Insignificant at 10% level.

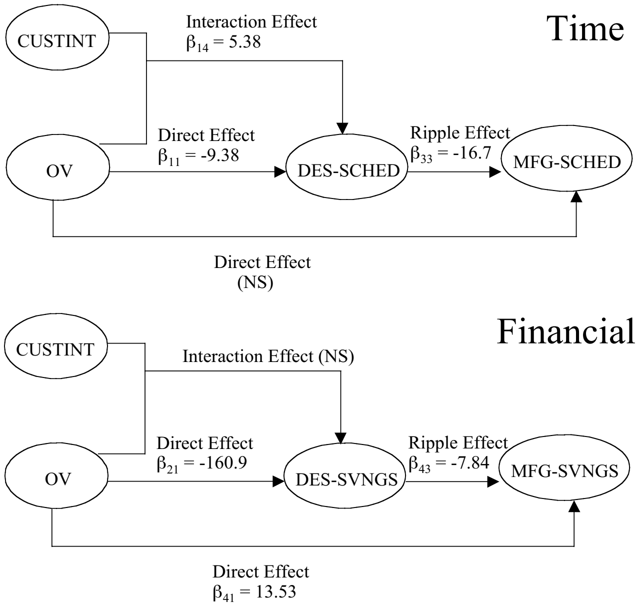
Finally, for Equation (4) (dependent variable MFG-SVNGS), we find support for both Hypotheses 4a and 4b, in the directions expected. Thus, OV affects MFG-SVNGS positively ($\beta_{41} = 13.53$), while SP affects it negatively ($\beta_{42} = -26.45$). Finally, we find support for Hypothesis 4g ($\beta_{43} = -7.84$), indicating that higher expenditures in design reduce downstream manufacturing costs. The managerial implications of this system of equations are described next.

4. Managerial Implications

Oversight. As can be seen from the system of equations, we examine three types of impacts of OV on the outcome metrics. These are: (a) the direct impact, (b) the interaction impact, and (c) the ripple impact of OV via intermediate metrics. Next, we elaborate on each of these in the context of Figure 1.

The direct impact (a) of OV on DES-SCHED and DES-SVNGS is found to be adverse. This suggests that a higher degree of oversight imposes a burden on the designers in terms of additional time spent on extraneous activities such as presentations and meetings, resulting in schedule slippage and cost overruns in the design phase. Time slippage in design could also be a result of activities that subsequently are beneficial in manufacturing. In either case, the direct effect of OV on DES-SCHED is adverse. From a manufacturing standpoint, MFG-SCHED is not found to be directly affected by OV. From a MFG-SVNGS perspective, however, a higher level of OV in the design phase does improve financial performance downstream. We attribute this to a greater recognition of downstream constraints and preferences of manufacturing, resulting in more efficient production.

Figure 1 **Marginal Effect of Increased Oversight on Project Performance**



Note that the estimates show that in contrast to its adverse direct impact, increased oversight, when coupled with increased customer interaction (impact b) is beneficial for the DES-SCHED. Project managers can leverage the customer interaction to impart a holistic perspective during the design phase. This systems approach leads to better coordinated design activities and lower levels of iterative design. This supports the discussion in Iansiti (1998) regarding the *T* role of project managers, who can bridge external system requirements, to internal development and achieve better schedule performance in design.

Finally, OV has a ripple impact (c) on downstream manufacturing metrics. For instance, MFG-SCHED is impacted by DES-SCHED, which in turn is affected by OV, arising from impact (a) above. Likewise, MFG-SVNGS is impacted by OV via the intermediate metric DES-SVNGS. The ripple effect of OV on MFG-SCHED suggests that while increased OV leads to time slippage in the design phase ($\beta_{11} < 0$), in contrast, MFG-SCHED, due to the ripple effect ($\beta_{33} < 0$), is positively impacted by increasing managerial oversight. This implies that the oversight activities in design have a beneficial impact downstream on manufacturing schedules. Likewise, the financial metrics in manufacturing (MFG-SVNGS) is also impacted favorably by DES-SVNGS, suggesting that increased OV leads to increased manufacturing efficiencies, from both the direct ($\beta_{41} > 0$) and ripple ($\beta_{43} < 0$) effects.

Having described the three marginal impacts of OV reflected in Figure 1, we next quantify the degree of the impact using the estimates of our model. We do this for a typical project with the choices of the managerial levers (independent variables SP, OV, CUSTINT) set at the mean values in our data set. The net marginal impact of OV on DES-SCHED is ($\beta_{11} + \beta_{14} \cdot \text{CUSTINT}$) from Equation (1). At the mean intensity of CUSTINT (=1.55), the marginal impact is $-1.041 = (-9.38 + 5.38 \cdot 1.55)$. The implication is that with higher levels of oversight, DES-SCHED slips. The downstream marginal impact of higher OV on MFG-SCHED (Equation (3)) is $= \beta_{33} \cdot (\beta_{11} + \beta_{14} \cdot \text{CUSTINT})$, arising from the ripple effect discussed earlier. Thus, the net marginal effect of OV on MFG-SCHED is $17.38 = (-16.7(-1.041))$. The substantial gains in manufacturing schedules indicate that investments in design time pay off in earlier completion of manufacturing tasks. Likewise, the marginal impact of OV on DES-SVNGS is negative ($\beta_{21} = -160.99$), and on MFG-SVNGS $= (\beta_{41} + \beta_{43} \cdot \beta_{21}) = 13.53 + (-7.84 \cdot -160.99) = 1{,}275.7$. This implies that financial performance in the design phase becomes more adverse, while manufacturing performance improves. The decision to increase or decrease OV thus depends on the relative magnitude of design and manufacturing budgets. Based on our data, the critical ratio of design to manufacturing, from a financial standpoint, is $1{,}275.7/160.99 = 7.92$.[7] This implies that managers should increase OV, as long as the design budget is less than approximately eight times the manufacturing budget.

Specialization. Specialization, as discussed earlier, speeds up the development process because of higher levels of expertise in designing individual subsystems. This is confirmed by the direct effect of SP on DES-SCHED (Equation (1)) and DES-SVNGS (Equation (2)). Even though specialist designers get paid more, this is more than offset by the increased efficiency from subsystem specialization in design. The interaction effect of SP with CUSTINT is also positive on DES-SCHED. This implies that specialists are able to use the input from customers to develop subsystems faster. However, the ripple effect of SP on downstream manufacturing is found to be adverse, both from a schedule and a financial standpoint. We attribute this to the narrow focus of specialists on their own subsystems, and consequent escalations in assembly costs in the manufacturing phase. Similar to the discussion on oversight above, our estimates suggest that, from a financial perspective, the intensity of SP should be reduced as long as design budgets are less than a critical ratio.[8]

The Effects of Customer Interaction. The effects of customer interaction during design have two opposing effects. The direct impact of CUSTINT on DES-SCHED is adverse, suggesting that increased customer contact does impose a burden in terms of delays in the first phase. The interaction impact of CUSTINT, however, mitigates this direct impact, as seen from the positive values of β_{14} and β_{15}. For a given level of OV and SP, the net marginal impact of higher intensity of CUSTINT is ($\beta_{13} + \beta_{14} \cdot \text{OV} + \beta_{15} \cdot \text{SP}$). In our study, the net impact of CUSTINT at the mean values of the levers was barely negative (-0.1394). The magnitude indicates that the direct and the interaction effects almost cancel each other. While on one hand activities related to customer interaction do delay the schedule, project managers and specialist designers are able to leverage these interactions with customers and accrue gains. The interaction of CUSTINT with OV leverages customer inputs from a systems perspective (brought by project managers). The interaction with SP likewise helps in speedier completion of subsystem design by specialist designers. Note that despite a slightly negative net effect on DES-SCHED, the ripple effect on manufacturing is positive, as seen from the negative value of β_{33}. The implication, therefore, from a schedule-management standpoint, is to increase the level of customer interaction and exploit the ripple effect. From the cost performance perspective, we observe an adverse direct impact of CUSTINT on DES-SVNGS, although it is not significant in our study.

Implications. This study suggests that managers select lower levels of specialization and higher levels of oversight for leveraging the payoffs downstream in manufacturing at the expense of higher resource consumption in design. These findings reinforce the DFM philosophy. We also caution that the strategy choice depends upon the relative resource consumption in the two phases. In our study, the critical ratio analysis indicates an overwhelming bias towards reaping benefits in manufacturing through increased oversight and reduced specialization in the design phase. Our model suggests a reversal of the above strategy for NPD projects where the design phase dominates the time and cost resource consumption. This would arise in new products that are innovative assemblies of purchased parts. In such environments, we recom-

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[7] Using a similar analysis, the critical ratio from a schedule standpoint is 16.7. This suggests that the manufacturing phase dominates unless the design schedule is more than 16.7 times the manufacturing schedule.

[8] Similar to the computation for the critical ratio for OV, the critical ratio for SP from a financial performance standpoint, is: $=(\beta_{42} + \beta_{43} \cdot \beta_{22})/\beta_{22}$.

mend reduced managerial oversight and increased intensity of specialization in design. The intensity of customer interaction in such environments should be selectively reduced by project managers to mitigate the adverse direct effects. One possible approach is to impose transaction costs on each interaction with the customer, thereby reducing the frequency of low-content exchanges.

5. Limitations and Future Work

One limitation of our study is the sample size. The specific and important information on the control variables enables us to provide significant managerial guidelines. However, such useful data collection often comes with the caveat of limited sample that restricts us from performing more rigorous analysis. For example, given the cross-sectional nature of the analysis, controlling for unobserved heterogeneity through project-specific intercepts would have been appropriate. Similarly, a more detailed model could have accounted for variance arising from customers, contents of projects, and characteristic management styles. However, even a parsimonious random effects cannot be applied due to lack of multiple observations for each project. We take comfort, however, from the fact that the parameter estimates in our model are quite stable across specifications. A second limitation is that our conclusions are based on analysis within a firm. A broader cross section of firms would enhance our ability to generalize. However, we believe the results are generalizable across firms, because the projects in our data set (a) were executed on geographically dispersed sites, (b) were managed by a variety of project managers, (c) were executed across time, and (d) had a variety of customers. Third, one could argue that variables such as oversight and specialization are endogenous rather than exogenous as in our model. In an applied setting, one has to make judicious choices in such classifications. Treating more variables as endogenous necessitates more instruments and increased data collection of additional variables, which may not be feasible in the field setting. Our model specification was motivated to unravel key relationships between managerial levers, of which managers at Missile Systems, Inc. were unsure. Clearly, the research in NPD that interfaces between marketing and operations, while widely considered important, has a limited theoretical basis thus far, which leads to competing hypotheses. As the cumulative weight of such evidence mounts, better theoretical frameworks will emerge. In future, we hope to collect similar data across other firms as well. The richer data set will enable us to more comprehensively support the findings reported here.

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