Risk management on complex product collaborative development with power asymmetry between supplier and manufacturer

Yanlu Zhao, Hui Cao[1]

Abstract

Risk management is a critical issue in complex product development, especially when suppliers are integrated. The power asymmetry between the supplier and manufacturer may largely influence the development process and affect the occurrence and interaction of risks, and it should be systematically examined. In this paper, we establish a structural model to study the impact of power asymmetry on risk occurrence in complex product collaborative development. Empirical data collected from engineers show that path coefficients of the risk structural model are significantly different between the manufacturer-advantaged situation and the supplier-advantaged situation. The results indicate that power asymmetry has significant effects on risk occurrence and interaction. Furthermore, we provide managerial insights into customized risk-reduction measures from the perspective of the discovered relationship difference.

Key words: risk management, complex product collaborative development, supplier involvement, power asymmetry, partial least squares

1. Introduction

Market competitions have placed an enormous amount of pressure on firms and pushed them to seek advantage by developing new products (Ernst & Fischer, 2014; Moon & Oh, 2014). Because the process of complex product development (CPD) is characterized as “innovative, creative and iterative” (Browning & Eppinger, 2002) and complex (Kardes *et al.*, 2013; Browning, 1998a), it proposes new challenges for product managers and engineers. For instance, because of a series of technical

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[1] Address correspondence to: Hui Cao, Department of Industrial Engineering, Tsinghua University. Email: caohui@tsinghua.edu.cn

uncertainties, the delivery of the Boeing 787 Dreamliner aircraft was delayed for more than three years and was billions of dollars over budget (Denning, 2013; Kardes *et al.*, 2013). Similar cases are reported frequently in the development of other complex products such as software (Oehmen *et al.*, 2014), automobiles, semiconductors (Osborne, 1993) and warfighters (Kardes *et al.*, 2013). Therefore, risk management plays a key role in enabling the success of CPD.

In CPD, risk management can be described as the process of risk analysis in the product development at the conceptual, preliminary and detail design stages, with respect to risk prediction, assessment and evaluation (Stapelberg, 2009). This analysis process in engineering design is both iterative and progressive (Sun, 2004). Reducing product development uncertainties is difficult due to the following barriers: product complexity, collaborative development, supplier involvement and power dependence (Browning, 1998a; Li *et al.*, 2014; Wasti & Liker, 1997; Gulati & Sytch, 2007). Prior studies suggested that firms tended to break the complex product into subsystems and outsourced the design work to external suppliers (Denning, 2013). This collaborative model forced the buyer to assume the role of original equipment manufacturer (OEM), which was popular for Boeing, Airbus and other aircraft manufacturers because OEMs and suppliers could share benefits and risks (Esposito & Passaro, 2009; Doerfler *et al.*, 2012). However, uncertainties arose with the involvement of external suppliers because of the apparent difficulty in communication, coordination, and knowledge sharing between the developers and because risk management would become tough and special (Kardes *et al.*, 2013; Li *et al.*, 2014; McIvor & Humphreys, 2004; Wynstra & Pierick, 2000). Moreover, the manufacturer with outsourcing capabilities would depend on the supplier’s technical strength and project experience or vice versa, considerably increasing dependence uncertainties (Gulati & Sytch, 2007). This mutual dependence can be deemed as a power, which is a scarce resource that organizations compete for, and its constructs strongly influence the decision-making process (Caniëls & Roeleveld, 2009). Gulati and Sytch (2007) reported that auto manufacturers would exploit weaker suppliers to obtain superior economic returns in the automotive industry. It might be easier for the advantaged side to identify and avoid risks; however, the disadvantage for its counterpart may increase the probability of risk occurrence.

The purpose of our study is to investigate how this power asymmetry between manufacturer and supplier would affect the risk behavior of the CPD process. In this case, we developed a structural model that described the relationship between causes and risks from the perspective of CPD. Then, we collected data and analyzed the difference between different power asymmetry situations. In the following sections, sections 2 and 3 provide the fundamental literature support to construct the risk model, sections 4 and 5 describe the methodologies and results for data collection and analysis, and section 6 discusses the results and draws some insightful implications for risk management in CPD.

2. Theoretical foundations

Feature of complex product development

The CPD process can be described as a complex network of interaction, some of which is based on the input from other parts or some of which precipitates a cascade of rework among activities (Browning & Eppinger, 2002). Factors that contribute to the complexity of product development consist of a long-term development cycle, the participation of numerous partners and contractors from multiple countries, the fluid nature of technologies deployed and the dynamism of external environments (Kardes *et al.*, 2013).

The CPD projects are also characterized by complexity, uncertainty, ambiguity, dynamic interfaces and time periods reaching a decade or more (Kardes *et al.*, 2013; Floricel & Miller, 2001). Miller and Lessard (2001) said, *large engineering projects are high stake games characterized by substantial irreversible commitments, skewed reward structures in case of success, and high probabilities of failure.* These difficulties and obstacles drive manufacturers to include suppliers into product development during the initial phase. For example, complex products, such as aircrafts, usually involve a necessary degree of outsourcing from suppliers simply because the manufacturers lack the necessary expertise in some areas, *e.g.*, engines and avionics (Tang *et al.*, 2009). Given the underlying complexity of new product development, it is not surprising that different types of intelligence and organizations are necessary for its success (Thomas, 2013).

Collaborative development by involving suppliers

Over the past decades, there have been extensive studies on integrating suppliers in the CPD process (Handfield *et al.*, 1999; Van Echtelt *et al.*, 2008). Scholars suggested that to construct an early and close relationship with suppliers was critical for manufacturers to succeed in product development (Cousins *et al.*, 2011; Najafi Tavani *et al.*, 2013). Early supplier involvement signified the utilization of joint capabilities to solve tough problems during the development process (Wagner & Hoegl, 2006). Collaboration with suppliers at the product design stage reduced the occurrence of design errors and also provided benefits to the testing and prototyping phases by sharing technical information early (Song & Di Benedetto, 2008). It enabled the manufacturers to shorten the development cycle, to increase the quality of new product launches and to introduce richer technologies into a new product (Najafi Tavani *et al.*, 2013; De Toni, 1999; Zsidisin & Smith, 2005).

However, empirical studies also found negative effects for supplier involvement in CPD (Thomas, 2013). A supplier's involvement may not always lead to improvements in efficiency (cost and time) and effectiveness (cost and quality), especially in an environment that undergoes significant changes or where a high degree of technical uncertainties exist (McIvor & Humphreys, 2004; Wynstra & Pierick, 2000). Hong and Hartley (2011) showed that encouraging suppliers to communicate did not have any effect on product development performance. Specifically, if the manufacturer cannot have direct control over the progress of technology, technical risk will increase. Moreover, the suppliers' early involvement into product development would increase the manufacturers' dependence and reliance on suppliers because the switching cost and technologies were highly restricted by the advantaged suppliers (Caniëls & Roeleveld, 2009).

Power asymmetry by involving the supplier

Involving the supplier in CPD in the early stage of design would cause the manufacturer to be more dependent on suppliers, which can be a source of power for the supplier and vice versa (Emerson, 1962). In aircraft design, component outsourcing in CPD is a fundamental strategic decision, which rejects the internalization of the development activities. If the manufacturer's power of technology and experience is weaker than the supplier's, the manufacturer will be dominated by the supplier in many aspects. Hence, before outsourcing, a manufacturer needs to recognize the power comparisons between both organizations in various dimensions because unequal dependence would cause power asymmetry, which is detrimental to the weaker side (Gulati & Sytch, 2007; Casciaro & Piskorski, 2005). Therefore, having a clear identification of one's own power position would be a prerequisite for the manufacturer and supplier to avoid risks in cooperation.

To evaluate the degree of power asymmetry, Jacobs (1974) used resource's "essentiality (whether A can do without B)" and "substitutability (whether other sources are available)" to measure the level of power asymmetry. Similarly, Gulati and Sytch (2007) conducted an exploratory factor analysis of thirteen items to reflect the different aspects of supplier and manufacturer power asymmetries. These items consist of technical strength, switching cost and economic demands.

Risk categories in CPD

In CPD, the activities of managing risks can be interpreted as a structured reduction of uncertainties (Oehmen *et al.*, 2014). Inevitably, the CPD process suffered from risks, such as cost overrun and schedule overrun, or problems in achieving the targeted technical performance (Francis *et al.*, 2010). In the case of the Boeing 787, the latest overheating battery problem in 2013 revealed serious technical risk, and Denning (2013) identified several risks through the case, including the sourcing risk and coordination risk, which were closely relevant with mutual dependence. Scholars also enumerated other types of risks, such as the degradation risk, market shift risk, need shift risk, program's stability risk and economic environmental risk (Miller &

Lessard, 2001; Carson *et al.*, 2012).

Among these categories, Browning (1998a) classified the typical risks in CPD into six categories: the product performance risk, technology risk, development cost risk, schedule risk, market risk, and business risk. Moreover, the requirement risk was identified as the most challenging risk at the initial design phase that needed thorough consideration (Zhang, 2013; Turner, 1990). Poorly identified and changing requirements would lead to an increase in costs and a delay of schedule because it is more costly to fix the problems in late development or production (Francis *et al.*, 2010).

To summarize, studies on risk management in CPD were discussed a few times in past years. Scholars studied the organizations of CPD projects, characteristics of CPD, and types of risks among CPD processes. However, we did not find any studies considering the impact of power asymmetry for risks in CPD. Therefore, this paper is devoted to investigating risk management in CPD with regard to the existence of power asymmetry.

3. Conceptual Model and Research Hypotheses

Studies suggested that companies who were successful in CPD need to construct a systematic conceptual model to manage risks (Browning, 1998a, b). To construct a systematic framework, five critical risks were captured and further exploited in this study, including requirement risk, technical risk, performance risk, schedule risk and cost risk. Literature and empirical studies showed that reducing these five types of risks were fundamental and significant to ensure product development success (Browning, 1998a; Tang *et al.*, 2009; Denning, 2013; Oehmen *et al.*, 2014; Raz *et al.*, 2002).

Requirement risk can be considered as uncertainty in the ability to fulfill the need or advocate for a design and the consequences thereof (Browning, 1999; Pahl *et al.*, 2007). It is the initial and fundamental element in CPD management. Studies showed that once a requirement was modified, numerous related modifications and risks arose (Francis *et al.*, 2010; Zhang, 2013; Michael, 2000). In this paper, we divide the principle causes of the requirement risk into two categories: the inner management of the manufacturer and the outer involvement of the supplier on the basis of their management process, communication and information interchange scope.

Technical risk is whether designers have the technological capabilities to design the product that can meet the performance criteria and the consequences thereof (Browning, 1999; Straub *et al.*, 2013). Previous studies have classified technical risk into four levels among which the highly technical risk projects are typical in situations where most of the technologies employed are new (Shenhar & Dvir, 1996). Following Browning (1998a) and Francis *et al.* (2010), in this paper, we model the technical risk in terms of technical feature and technical maturity.

Performance risk is the uncertainty that the product design can meet the desired quality criteria and the consequences thereof (Schmidt & Calantone, 1998; Browning, 1999). It evaluates the quality of the product design. Therefore, we attribute the uncertainties of the product performance to the number of iterations (Browning, 1998a) and the accelerated design and defect check mechanism.

Schedule risk is the uncertainty associated with the ability of a project to develop an acceptable design within a span of time and the consequences thereof (Browning, 1998b; Straub *et al.*, 2013). It is a common risk in product development and is often described as project delays or delivery postponement (Carson *et al.*, 2012; Francis *et al.*, 2010). In this paper, we consider that the schedule risk is mainly affected by plan feature, product feature, and accelerated design, as described by Browning (1998b).

Cost risk is an inevitable risk. Very few development projects have claimed that its eventual expenses were less than the initial budget (Oehmen *et al.*, 2014; Francis *et al.*, 2010). Generally, cost risk is a passive risk caused by other risks, *e.g.*, requirement modification, performance defects or schedule delays (Browning, 1998a). In our model, we consider cost risk as a passive risk, which is affected by its relevant risks.

Although engineers described a variety of other risks that might occur in CPD, *e.g.*, the patent risk (Ernst & Fischer, 2014), we decided to limit our model to these five critical risks and neglected the other risks because literature and empirical studies showed that other risks were not typical in CPD (Browning, 1998a; Denning, 2013).

Based on the identified risks and their causal factors, we constructed a risk model to describe their relationship. All of these preparations were used to observe how the power asymmetry between manufacturer and supplier would affect their correlations to the risk model or the different relationships in manufacturer-advantaged and supplier-advantaged scenarios. These differences have not been discussed previously, so we wish to discover some useful management insights for managers and engineers to reduce the occurrence of risk in CPD.

Conceptual risk model

We construct the conceptual risk model as two parts: the exogenous part and the endogenous part. The former part is the framework that describes the causes of each risk and whether this relationship is significant; the latter part emphasizes the interaction among risks and indicates that it is necessary to manage the risks from a systematic perspective. The model is illustrated in Figure 1 and Table 1.

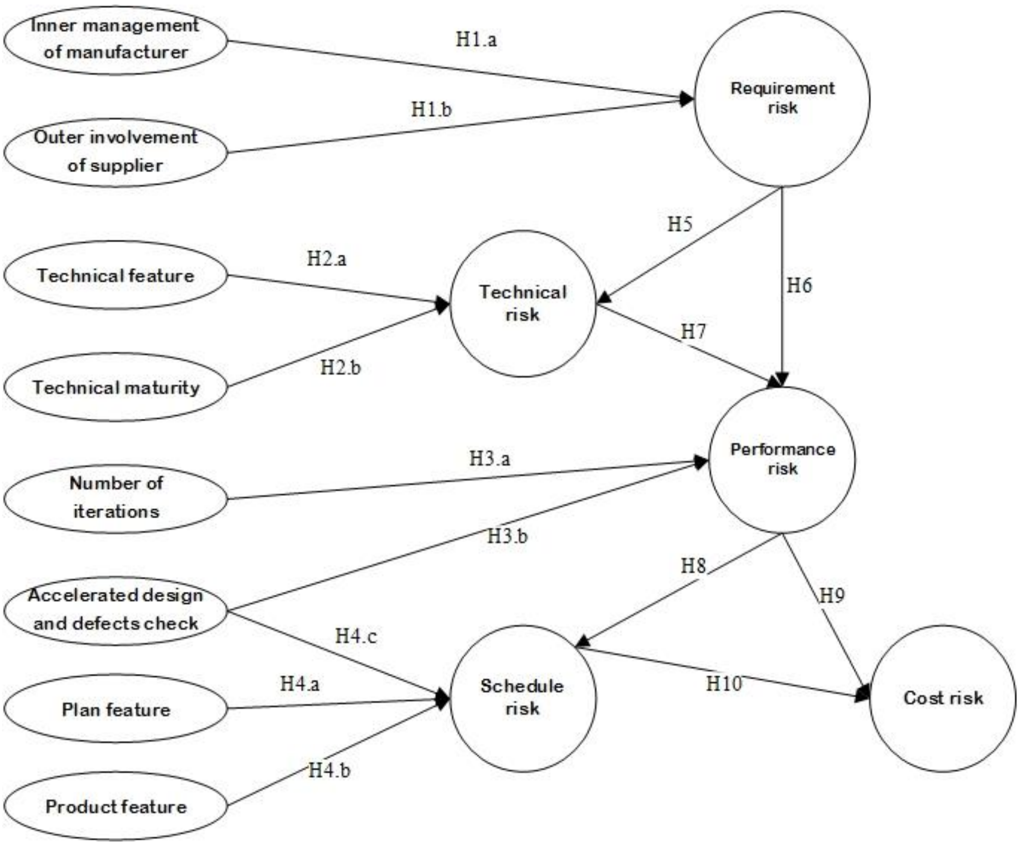

Figure 1 Conceptual risk model in complex product development

(I) Exogenous model

Causes of requirement risk. Design requirements are identified before the concept proposition and would not be frozen until the end of design (Pahl *et al.*, 2007; Zhang, 2013). Early studies showed that more than 80 percent of a development project's resources were committed within the first 20 percent of the new product life cycle (Westinghouse, 1984). Therefore, it is necessary to define the requirement as complete and accurate as possible in the initial period. Because systematic methodologies used for defining requirements are not extensive, the information actually available during the conceptual design is vastly different from the information needed by designers. Elucidating the design requirement is the first and one of the most difficult troubles in CPD (Michael, 2000).

Table 1 Risk factors and its measured indicators

Factors	Indicators
Inner management of manufacturer	standard process and file
	experts' assessment mechanism
	verification and validation testing
Outer involvement of supplier	requirement transfer degree
	degree of supplier digesting requirement proposition
	communication and feedback
	requirement management information system
Technical feature	organization and professional
	monopolized technology
	technical strength
Technical maturity	lifecycle technology
	compatible technology
	technology novelty
Number of iterations	number of iterations
Accelerated design and defect check	accelerated design in supplier
	accelerated design in manufacturer
	concealed defects
	verification and validation regulations
Plan character	scientific schedule
	communication and coordination
	activity completeness
	activity sequencing quality
Product feature	degree of activity coupling
	product and process novelty
Requirement risk	requirement modification

Technical risk	technique prediction
Performance risk	function missing
	product defects
Schedule risk	schedule delay
Cost risk	cost overrun

Empirical studies showed the values of a transparent requirement defining process including requirement building, process checking and error proofing (Oehmen *et al.*, 2014; Carson *et al.*, 2012). All of these operational factors were inherent for the manufacturer and critical to any requirement defining work in CPD. However, if the complex product is collaboratively developed with the supplier, it is necessary to consider the factors of supplier review and guidance (Browning & Ramasesh, 2007; Browning, 1998a), coordination (Lam & Chin, 2005), knowledge sharing (Li *et al.*, 2014), collaborative information system (Bendoly *et al.*, 2012), and communication and feedback (Denning, 2013; Browning, 1998a) when discussing requirement risk causes. We summarize these factors as the inner management of the manufacturer and the outer involvement of the supplier, and thus, we obtain Hypothesis 1:

Hypothesis 1.a: In CPD, inner management of the manufacturer is negatively related to the occurrence of requirement risk.

Hypothesis 1.b: In CPD, outer involvement of the supplier is negatively related to the occurrence of requirement risk.

Causes of technical risk. Technical risk is described as "the risk of being able to solve any remaining problems adequately, the risk of having the necessary competencies and complementary technologies required for commercialization, and the risk of achieving the technical specifications necessary to meet customer expectations" (Hartmann & Myers, 2003). These competencies and technical problem solving capabilities can be summarized as technical features, including technical strength and the monopolization of technology employed in CPD. However, once a complex product is collaboratively developed with suppliers, the manufacturer cannot overlook the potential uncertainties brought by the outsourcing suppliers (Oehmen *et al.*, 2014; Temponi & Lambert, 2001). Additionally, the manufacturer might be constrained by the supplier with stronger technical acumen (Li *et al.*, 2014), which is an important factor to determine the manufacturer's dependence on the supplier (Gulati & Sytch, 2007). In addition, if the supplier adopts monopolized technology to design core systems, it even restricts the selection of potential suppliers, further decreasing the bargain power of the manufacturer (Browning, 1998a; Caniëls & Roeleveld, 2009). Therefore, these technical features are the main causes of technical risk and are also closely related to the power asymmetry between the manufacturer and supplier. Moreover, most of the technical uncertainties stem from the immaturity of the technologies employed (Browning, 1998a). Technical maturity can be evaluated by the novelty of the technology, proficiency of the technology and compatibility of the technology. High-risk projects have critical, undeveloped technologies on their critical path, or they employ many new technologies. These projects are characterized by long periods of design, development, testing, and redesign (Raz *et al.*, 2002). Therefore, we propose Hypothesis 2 as follows:

Hypothesis 2.a: In CPD, a technical feature is negatively related to the occurrence of technical risk.

Hypothesis 2.b: In CPD, technical maturity is negatively related to the occurrence of technical risk.

Causes of performance risk. Performance risk is the potential loss incurred when a brand or product does not perform as desired or expected (Horton, 1976; Schmidt & Calantone, 1998). It usually involves a tradeoff between the improvements in product performance and the reduction of NPD cycle time (Cohen *et al.*, 1996). Performance is mainly determined by the iterations, accelerated design and defect checking mechanism. Intentional iterations are planned, refining the designs and allowing the performance to converge to a desirable solution (Browning, 1999). Successive iterations would move the design closer to the desired targets (Smith & Eppinger, 1997). However, once the design process is accelerated, some procedures can be neglected, increasing the performance risk (Browning, 1998b). Moreover, if the design errors and incompatibilities are discovered downstream, they would affect the upstream development process heavily (Browning, 1998a). Therefore, it is better to define the defect checking and error-proofing process and mechanism (Oehmen *et al.*, 2014). These problems lead to Hypothesis 3.b. Additionally, the occurrence of performance risk is driven by a lack of information regarding inputs to the development project such as requirement specifications and technologies (Nidumolu, 1995). We will address this issue in the exogenous part.

Hypothesis 3.a: In CPD, the number of iterations is negatively related to the occurrence of performance risk.

Hypothesis 3.b: In CPD, the accelerated design and lack of a defect-checking mechanism is positively related to the occurrence of performance risk.

Causes of schedule risk. Case studies from Boeing and Intel have indicated that schedule risk was inevitable in CPD (Smock, 2009; Osborne, 1993) because iterations (especially unintentional) and rework frequently occurred to converge to the requirement specification (Novak & Eppinger, 2001). Since the 1950s, numerous scholars studied the method to develop scientific plans for development processes, such as PERT, CRM, and DSM (Eisner, 1962; Elmaghraby, 1964; Browning & Eppinger, 2002), to reduce schedule overruns caused by unintentional and unexpected rework. The product development process is often modeled as an activity network; thus, any missing or wrong sequencing activities would create new information, which would also alter assumptions and cause upstream activities to repeat (Browning, 1998a). Therefore, the factors affecting schedule can be summarized as the planning feature (unintentional iterations, scientific plan technique, degree of interweaving activities and sequence of activities). Moreover, in terms of the product feature, the complexity and novelty of the new product would significantly affect the project schedule. Generally, a complex product typically exhibits coupling or interconnection among their components, implying complex development processes (coupled activities) and organizations (coupled teams) (Browning, 1998b). Moreover, an accelerated design has a positive effect on the schedule by weeding out those less important activities (Browning, 1998b). Therefore, the hypotheses are described as follows.

Hypothesis 4.a: In CPD, the plan feature is negatively related to the occurrence of schedule risk.

Hypothesis 4.b: In CPD, the product feature is positively related to the occurrence of schedule risk.

Hypothesis 4.c: In CPD, the accelerated design and lack of defect-checking mechanism is negatively related to the occurrence of schedule risk.

(II) Endogenous model

Having described the exogenous model in the previous section, we discuss the endogenous model in this part. The endogenous model describes the interaction between risks.

The requirement risk is a principle driver of other risks. It is the "blustering fuse" in the risk chain. Many studies emphasized the importance of reducing the occurrence of requirement risk (Thomas, 2007; Pahl *et al.*, 2007; Francis *et al.*, 2010). However, elucidation of the requirement in the initial phase is notoriously difficult and unpractical (Michael, 2000; Nidumolu, 1995). The consequences of requirement risk are missing requirements, defects (Alshazly *et al.*, 2014), ambiguity, overestimated/ underestimated requirements and non-implementability (Walia *et al.*, 2009; Michael, 2000). These requirement defects are tightly connected with technical risk, which are related to the requirement implementation in product design (Raz *et al.*, 2002), such as the changing of technology for an underestimated requirement in the initial design phase. The requirement proposed by engineers without rich technical experience would typically encounter many technical problems during implementation. This leads to Hypothesis 5.

Hypothesis 5: The occurrence of requirement risk is a highly probable cause of the occurrence of technical risk.

Performance risk is the pivotal risk among risk interactions. There are two types of uncertainties that would affect performance risk: the requirement uncertainties and the technical uncertainties (Nidumolu, 1995). Incomplete, ambiguous or inconsistent requirements or their frequent changes would make the performance outcomes hard to predict (Thayer & Lehman, 1977; Berkeley *et al.*, 1990). Regarding the technical uncertainties, the use of "complex or state of the art technologies" and technical changes causing system design modification have been identified as key sources of project uncertainties (Zmud, 1980). McFarlan (1981) viewed the lack of an organization's experience with technology as another key source of uncertainties. Therefore, the complexity of technology increases the performance risk in addition to the technical change and novel technology usage (Zmud, 1980; Beath, 1983). This leads to Hypothesis 6 and Hypothesis 7.

Hypothesis 6: The occurrence of requirement risk is a highly probable cause of the occurrence of performance risk.

Hypothesis 7: The occurrence of technical risk is a highly probable cause of the occurrence of performance risk.

Most schedule risk studies focused on the exogenous factors that we just discussed in the previous section. However, recent studies revealed that the product's outcome significantly affects the duration of development (Oehmen *et al.*, 2014). For example, product design quality would be improved by successive iterations, a key driver of cost and schedule risk in NPD (Browning & Eppinger, 2002; Safoutin & Smith, 1996; Whitney, 1990). It is inevitable to postpone the delivery of product if performance cannot meet the requirement specifications (Thomas, 2007). This leads to Hypothesis 8.

Hypothesis 8: The occurrence of performance risk is a highly probable cause of the occurrence of schedule risk.

Cost risk is a final form of risk occurrence. As Thomas (2007) said, technical risk and performance risk are both monetary in nature. Moreover, cost risk is a passive risk, which is tightly related with other active risks (Browning, 1999; Oehmen *et al.*, 2014). Studies revealed that 70% of the lifecycle cost is locked in the design stage, so design for cost has great potential to reduce cost overrun (Thomas, 2007). Development costs are tightly related with the product performance because performance defects that demand rework and iterations would need additional capital and human resources (Oehmen *et al.*, 2014). Because schedule is one of the constraints for product design, sometimes managers and engineers would prefer to trade money for time to complete the expected design work as the original plan (Browning, 1998a). This leads to Hypothesis 9 and Hypothesis 10.

Hypothesis 9: The occurrence of performance risk is a highly probable cause of the occurrence of cost risk.

Hypothesis 10: The occurrence of schedule risk is a highly probable cause of the occurrence of cost risk.

Power asymmetry on conceptual risk model

When previous studies investigated the causes of risk occurrence in product development, few of them took the power asymmetry between supplier and manufacturer into the consideration for risk causes and interaction. However, interviews with engineers and managers indicated that this power asymmetry can influence the risk occurrence. For example, if the manufacturer is comparatively dependent on the supplier, it may cause more risks in terms of the resource dependence theory (Salancik & Pfeffer, 1978) and transaction cost theory. For another instance, if the manufacturer is able to dominate suppliers and controls their design processes, risks could be identified earlier and could be controlled well. However, if the supplier has the power advantage, the scope of uncertainties may be beyond the control of the manufacturer, which increases the potential threats. Moreover, the interaction of risk occurrence can change considerably in a power asymmetry situation. After incorporating the supplier into product development, the risk model should be adjusted from the perspective of power asymmetry. To further explore the influence brought by power asymmetry, we simply proposed that the *causal* *relationship and interaction relationship described in H1-H10 are adjusted by power asymmetry between the manufacturer and supplier, namely, the proposed conceptual risk model under manufacturer-advantaged (MA) is significantly different from that under supplier-advantaged (SA).*

In this paper, power asymmetry is described by several measurements, including technical strength, dependence, economic impact, and the number of alternative suppliers. Most of these measurements are referred to in prior research (Gulati & Sytch, 2007) and are summarized in Table 2.

Table 2 Measurements of Power and Dependence

No.	Measurement	Survey Item
1	Technical experience assistance	Supplier's technical experience can help your firm considerably for the technology employed in product development
2	Project management assistance	Supplier's project management ability can help your firm considerably in controlling resource allocation and schedule in the development project
3	Cost management assistance	Supplier’s cost management ability can help your firm considerably in controlling cost in the development project.
4	Technical advantage	For the development work, supplier’s technical ability is more advantaged than yours.
5	Supplier technical competency	For the development work, supplier’s technical ability is more advantaged than other potential suppliers.
6	Availability of potential suppliers	There is more than one supplier that can provide the technology and product to satisfy you.
7	Manufacturer’s switching cost	It would take considerable money and time if you change your supplier.
8	Availability of alternate short term storage	If you want to change your supplier, there is adequate time for you and your company to find another supplier.
9	Supplier’s withdrawal cost for manufacturer	The unexpected end of cooperation between you and your supplier would bring considerable expense to you.
10	Manufacturer’s withdrawal cost for supplier	The unexpected end of cooperation between you and your supplier would bring considerable expense to supplier.
11	Supplier’s withdrawal delay for manufacturer	The ending cooperation between you and your supplier would bring considerable and unfavorable effects to your schedule.
12	Dependence	You are dependent on the supplier.
13	Dependence	Supplier is dependent on you.

4. Methodology

To test the proposed risk model, we developed a questionnaire to collect data. Items were selected either by adapting measures that have been validated by previous studies or by converting their definitions into question format (Bock *et al.*, 2005). The questionnaire was pretested and reviewed by a team of industrial experts and academics. Each factor in our model was measured with a block of measurements (questionnaire items). Items of risk identification were adapted from Browning (1998b, 1999) and other scholars' studies (Nidumolu, 1995). Please refer to the Appendix to see the detailed questionnaire. All items were measured by a seven-point Likert scale ranging from "strongly disagree" to "strongly agree", with "neither agree nor disagree" as a midpoint (Chin & Dibbern, 2010).

Based on the questionnaire, we interviewed 64 engineers and managers from 17 CPD teams. Each interview lasted approximately two hours. During the interview, we explained each question in the questionnaire to the participant in detail to ensure a quality response. Out of the 64 responses, four responses with incomplete data were eliminated from further analysis. Based on the 60 responses, we examined our hypotheses by using a partial least squares (PLS) method and analyzed the difference in path coefficients affected by power asymmetry, which are discussed in the following section.

5. Statistical Analysis and Results

Partial least squares (PLS) modeling has gained considerable attention among scholars in recent years. It is widely used because it allows "latent constructs to be modeled either as formative or reflective indicators as was the case with survey data" (Bock *et al.*, 2005), and it demands a considerably smaller sample size to validate a model versus the alternative covariance-based structural equation modeling techniques, especially for complex models (Chin & Newsted, 1999). We used the software Smartpls version 2.3 for the PLS analysis.

To explore the impact of power asymmetry on risk occurrence, we examine the model with two samples G_1 and G_2. G_1 denotes the group of samples in which the manufacturers have a power advantage (MA), and G_2 denotes the group of samples in which the suppliers have a power advantage (SA). Data for G_1 and G_2 are drawn from the original survey data by classification in terms of measurements of power, as described in the previous section. G_1 and G_2 consist of 22 and 38 responses, respectively. By applying the PLS analysis on G_1 and G_2, the measurement model and structural model for each sample set are obtained. To clarify the impact brought by power asymmetry, the difference in the path coefficients (P_1 and P_2) in the PLS parameter estimation is tested with null hypothesis H_0, which proposes that there is no difference between P_1 and P_2 (*i.e.*, $P_1 = P_2$). The hypotheses are tested by examining the magnitude of the standardized parameter estimates between constructs together with the corresponding *t*-values that indicate the level of significance. The *t*-values are obtained by using the bootstrap method.

Table 3 Results for Convergent validity tests of each group

Factors	Items	MA		SA	
		CR*	AVE*	CR	AVE
Inner management of manufacturer	3	0.9469	0.8562	0.8121	0.5936
Outer involvement of supplier	4	0.8341	0.5623	0.8983	0.6965
Technical feature	3	0.8653	0.6849	0.7376	0.5086
Technical maturity	3	0.8644	0.6815	0.7945	0.5653
Number of iterations	1	1.0000	1.0000	1.0000	1.0000
Accelerated design and defects check	4	0.9111	0.7207	0.7948	0.4999
Plan feature	4	0.8332	0.5630	0.8859	0.6843
Product feature	2	0.9741	0.9495	0.7918	0.6553
Requirement risk	1	1.000	1.0000	1.0000	1.0000
Technical risk	1	1.000	1.0000	1.0000	1.0000
Performance risk	2	0.9116	0.8376	0.9729	0.9473
Schedule risk	1	1.0000	1.0000	1.0000	1.0000
Cost risk	1	1.0000	1.0000	1.0000	1.0000

*Convergent validity requires $CR \geq 0.6$, $AVE \geq 0.5$ in each column.

Measurement Model. To check whether the indicators of each construct can measure the corresponding variables, tests for convergent validity and discriminant validity are performed for each group. Convergent validity is measured by examining the composite reliability (CR) and the average variance extracted (AVE) from the measurements. When CRs and AVEs are no less than the thresholds of 0.6 and 0.5, the convergent validity of the sample data is sufficient for further analysis (Chin & Dibbern, 2010). The results of the convergent validity tests are shown in Table 3, which shows that the above criteria are met for each factor. The discriminant validity of the constructed items are verified by checking whether the square root of the AVE for each construct is greater than the correlations between the constructs, recommended by Fornell and Larcker (1981). The results in Table 4 and Table 5 confirm the discriminant validity of each construct.

Structural Model. The results of the PLS analysis are depicted in Figure 2 and are summarized in Table 6. Figure 2 showed the comparing coefficients of each path in the causes-risks graph with its significance indicated by the number of stars. Table 6 summarized the variables of each pair for cause and risk. For each pair of variables, its path coefficient and significance in each situation were described in columns 4 through 7. The last two columns showed the path difference in MA and SA.

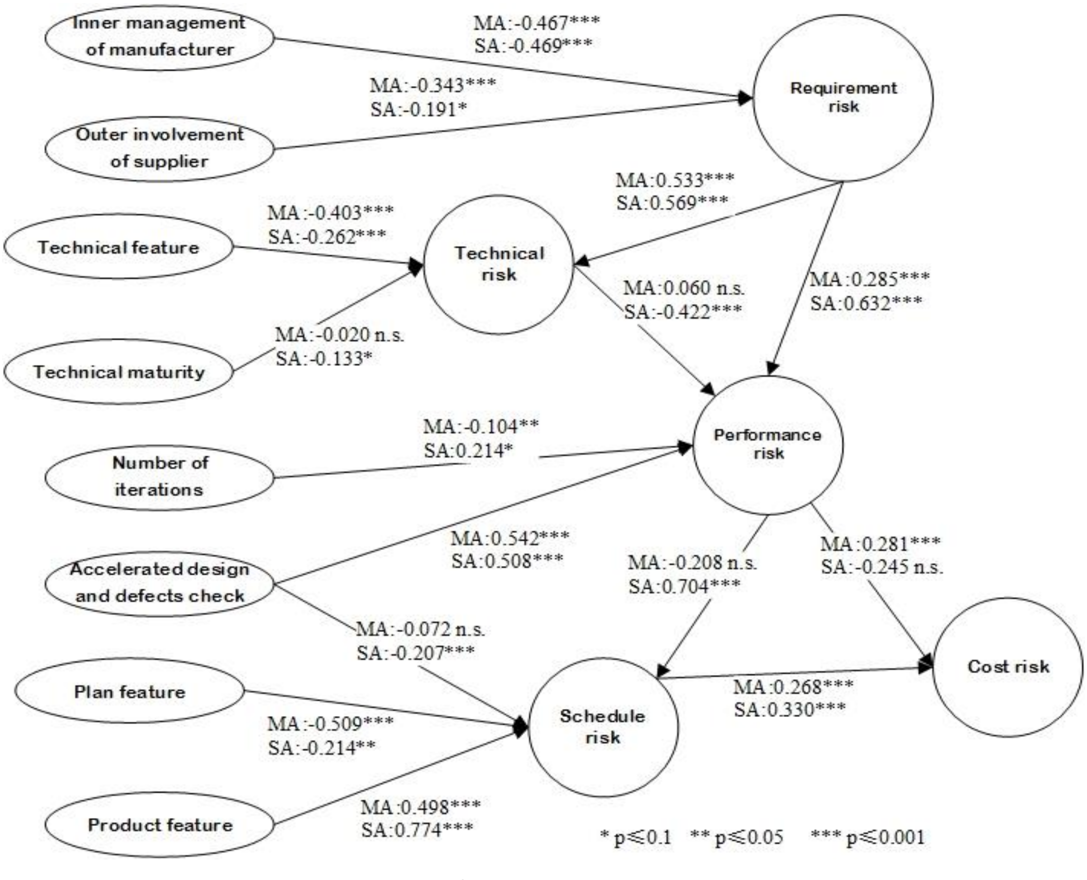

Figure 2 Comparison results of structural model adjusted by power asymmetry

Table 4 Correlation between constructs in MA sample

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Inner management of manufacturer	0.770												
2. Outer involvement of supplier	-0.194	0.835											
3. Technical feature	0.283	-0.466	0.713										
4. Technical maturity	0.102	-0.344	0.647	0.752									
5. Number of iterations	0.102	-0.177	0.195	0.288	single								
6. Accelerated design and defects check	-0.549	0.272	-0.456	-0.163	-0.078	0.708							
7. Plan feature	-0.190	0.319	-0.409	-0.229	-0.184	0.078	0.827						
8. Product feature	-0.304	0.028	-0.085	-0.116	-0.318	0.321	0.352	0.810					
9. Requirement risk	-0.401	-0.252	0.092	-0.181	-0.395	0.166	0.192	0.386	single				
10. Technical risk	-0.034	-0.184	-0.367	-0.377	-0.352	0.115	0.350	0.334	0.500	single			
11. Performance risk	-0.352	0.074	-0.286	-0.080	-0.321	0.512	0.203	0.347	0.466	0.364	0.973		
12. Schedule risk	0.091	-0.461	0.538	0.520	0.408	-0.081	-0.347	0.226	0.120	-0.237	-0.114	single	
13. Cost risk	-0.500	0.186	0.132	0.271	-0.112	0.483	0.257	0.348	0.396	-0.027	0.189	0.238	single

1. “Single” means the construct is a single item, and the square root of AVE is one.

2. Discriminant validity requires that the value in the diagonal is no less than the correlations in its column.

Table 5 Correlation between constructs in SA sample

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Inner management of manufacturer	0.925												
2. Outer involvement of supplier	0.760	0.750											
3. Technical feature	0.261	0.486	0.828										
4. Technical maturity	0.480	0.745	0.526	0.826									
5. Number of iterations	0.181	-0.229	-0.172	-0.180	single								
6. Accelerated design and defects check	-0.618	-0.469	-0.106	-0.481	-0.030	0.849							
7. Plan feature	-0.696	-0.431	-0.231	-0.494	-0.544	0.728	0.750						
8. Product feature	-0.702	-0.295	0.029	0.026	-0.191	0.382	0.545	0.974					
9. Requirement risk	-0.614	-0.547	-0.437	-0.545	-0.452	0.345	0.741	0.256	single				
10. Technical risk	-0.527	-0.521	-0.580	-0.580	-0.024	0.566	0.684	0.341	0.755	single			
11. Performance risk	-0.241	-0.390	-0.321	-0.271	-0.122	0.412	0.504	0.209	0.409	0.326	0.915		
12. Schedule risk	-0.370	-0.146	-0.373	0.004	-0.035	0.266	0.395	0.671	0.204	0.320	0.597	single	
13. Cost risk	-0.892	-0.483	-0.088	-0.318	-0.499	0.465	0.721	0.667	0.619	0.442	-0.025	0.185	single

Table 6 Results for power asymmetry group comparisons

Independent Variable	Dependent Variable	Hypothesis	MA		SA		Group Difference	
			path	t-value	path	t-value	path	t-value
Inner management of manufacturer	Requirement risk	H1.a(+)	-0.467	5.524	-0.469	4.479	0.002	0.012
Outer involvement of supplier	Requirement risk	H1.b(-)	-0.343	5.152	-0.191	1.720	-0.152	1.696
Technical feature	Technical risk	H2.a(-)	-0.403	4.250	-0.262	3.963	-0.140	1.222
Technical maturity	Technical risk	H2.b(-)	-0.020	0.239	-0.133	1.609	0.113	0.959
Number of iterations	Performance risk	H3.a(+)	-0.104	1.812	0.214	1.327	-0.318	2.230
Accelerated design and defects check	Performance risk	H3.b(+)	0.542	5.583	0.508	3.960	0.034	0.261
Plan feature	Schedule risk	H4.a(-)	-0.509	5.080	-0.214	1.843	-0.295	1.900
Product feature	Schedule risk	H4.b(+)	0.498	4.920	0.774	9.612	-0.276	2.274
Accelerated design and defects check	Schedule risk	H4.c(-)	-0.072	1.149	-0.207	0.944	0.136	0.900
Requirement risk	Technical risk	H5(+)	0.533	6.772	0.569	6.635	-0.036	0.308
Requirement risk	Performance risk	H6(+)	0.285	3.225	0.632	4.307	-0.347	2.076
Technical risk	Performance risk	H7(+)	0.060	1.385	-0.422	2.910	0.482	3.039
Performance risk	Schedule risk	H8(+)	-0.208	1.302	0.704	6.403	-0.912	7.251
Performance risk	Cost risk	H9(+)	0.281	2.489	-0.245	1.606	0.526	3.355
Schedule risk	Cost risk	H10(+)	0.268	3.662	0.330	2.306	-0.062	0.408

6. Discussion

Significance of Group Differences

The PLS analysis shows that our empirical experiences are consistent with hypotheses H1.a, H2.a, H3.b and H5, and there are no significant differences between MA and SA for these four hypotheses. Moreover, hypothesis H2.b is not significant in both cases. The other results can be divided into two categories: consistent with the hypothesis but significantly different between MA and SA and inconsistent with the hypothesis and significantly different. We will discuss the results in detail hereafter.

(I) Consistent with hypothesis but significantly different between MA and SA

This category includes hypotheses H1.b, H4.a, H4.b and H6. The empirical research supports the hypotheses in both MA and SA cases; however, their path coefficients for MA and SA differ significantly.

H1.b implies that the improvement of the involved suppliers’ requirement management capability would reduce the requirement risk. When considering the power asymmetry, the original requirement management capability of the supplier in SA is usually higher than that of the supplier in MA. According to the law of diminishing marginal utility, the marginal benefits brought by supplier improvement would be less for SA compared to MA. In this case, enhancing the requirement management ability of the involved suppliers in MA can result in more benefits compared with that in SA.

The plan feature is negatively related to the occurrence of schedule risk (H4.a). Our analysis shows that this negative correlation differs between MA and SA. In MA, the manufacturer has the ability to dominate the development process and can push the supplier to follow their schedule. However, when the supplier’s power is greater, the supplier may dominate the development process instead, and the schedule could proceed beyond the manufacturer’s control. In this case, improving the plan feature may be less effective for reducing schedule risk in SA. Therefore, in SA, manufacturers may need to spend more resources in planning for reducing the schedule risk occurrence.

The level of correlation between product feature and the occurrence of the schedule risk (H4.b) is also significantly different between MA and SA. In collaborative development, the selection of supplier should consider the complexity and novelty of products. Compared to SA, a manufacturer has better control of the development schedule in MA. In this case, an increase in difficulties during development would provide less schedule risk for the manufacturer in MA than in SA. Moreover, the more complex the product is, the stronger the supplier selection tends to be. An advantaged supplier means a more complex product to develop, which would provide more schedule risk because of its complexity. As a result, in SA, a manufacturer should make additional effort to reduce the schedule risk caused by the product feature than in MA.

The occurrence of requirement risk is positively related to the occurrence of performance risk (H6), and this correlation in SA is greater than that in MA. Reasons for this difference can be summarized as follows. The manufacturer could handle the supplier more easily when it is power advantaged. As a result, once the requirement risk occurs, the manufacturer in MA can push the supplier to cooperate to solve the requirement problem, while the manufacturer in SA has less capability. In this case, the requirement risk in SA tends to result in a more vulnerable performance than MA.

(II) Inconsistent with hypothesis and significantly different between MA and SA

The path coefficients in this category are significantly different between MA and SA, and one path in each pair is contrary to the hypothesis. This category consists of hypotheses H3.a, H7, H8, H9, and H10.

The number of iterations is negatively related to the occurrence of the performance risk in MA (H3.a), but this negative correlation is not supported when the supplier is advantaged. In MA, the manufacturer dominates the product development process, and the increase in intentional iterations would reduce performance risk. However, in SA, many iterations are likely unintentional for the manufacturer, who lacks the ability to control the overall product development process. Therefore, the result suggests that the manufacturer needs to pay attention to unintentional iterations, which would cause the performance risk to occur more often.

Previous literature stated that technical risk was positively related to the performance risk. However, the empirical study in this paper shows that technical risk is negatively related to the performance risk in SA (H7). The reason for this can be traced back to supplier selection. When the manufacturer predicts high technical uncertainties during product development, it may prefer to select a supplier with stronger technical power, which would help the manufacturer reduce its performance risk. As a result, in MA, a manufacturer needs to manage technical risk by himself because it cannot be solved with the assistance of a weak supplier.

For the relationship among performance risk, schedule risk and cost risk, we can see that the correlation between schedule risk and cost risk (H10) is significant in both cases. In MA, the correlation between performance risk and schedule risk (H8) is not significant, but the correlation between the performance risk and the cost risk (H9) is. However, in SA, the correlation between performance risk and schedule risk (H8) is significant, but the correlation between performance risk and cost risk (H9) is not significant. This suggests that once performance risk occurs, a manufacturer would like to devote/allocate extra resources and engineers to solve the problems, while the supplier tends to maintain the original amount of resources. Therefore, in MA, the problem can be solved within the original schedule at an increased cost. However, when the supplier dominates the CPD process, without extra resources, schedule overruns and cost overruns will occur.

Theoretical implications

The principle contribution of this study is to substantiate that power asymmetry between the manufacturer and supplier would greatly affect the risk occurrence in CPD. Currently, it is a trend to outsource in the CPD process because the complexity of the product determines that it is tough to fulfill the tasks independently. This outsourcing strategy inevitably provides mutual dependence and power asymmetry between the manufacturer and the supplier. However, previous studies paid little attention to power asymmetry in CPD, and no study has considered the power asymmetry when dealing with risks. In our study, we demonstrate that the risk causes-risks relationship differs significantly between the MA and SA cases. In this case, the risk management activities should consider the power asymmetry between manufacturers and suppliers.

Managerial implications

Historical studies showed that supplier management plays a vital role in the success of complex product development and that the risks in CPD need to be carefully managed. In this research, we also reveal that managers need to adjust their supplier selection and risk management strategies in terms of power asymmetry, whose existence provides unexpected factors that cause risks. The joint development of complex products with competitive suppliers would help the manufacturer take advantage of the technology capacity and project experience of the suppliers. However, overdependence on suppliers also causes difficulties in managing them during CPD process. Therefore, it is necessary for managers to tradeoff between the capability of the suppliers and the controllability of the CPD process when they select suppliers.

An additional question needs to be answered: what types of risk-reduction measures should be taken when the supplier/manufacturer is advantaged? Our study shows that managers need to use additional efforts in risk management when the supplier is advantaged. Specifically, for requirement risk induced by supplier involvement, a manufacturer should address the communication and requirement transfer, including constructing regulations and information systems. Similarly, for schedule risk led by product feature and plan feature, a manufacturer should divide its development activities systematically and scientifically in terms of product complexity and activity feasibility, to reduce the schedule risk occurrence caused by unexpected incidents. When a manufacturer is advantaged, it needs to determine the risk management strategies based on its own leadership and the suppliers' dependence. For example, a manufacturer should supervise technical uncertainties by arranging iterations with the balance of product performance and schedule. In a word, the results in this research suggest the managers should take the customized risk reduction measures out of their power position to help the manufacturer develop complex products smoothly.

Limitations and implications for future research

The data utilized in this paper were collected from manufacturers in China. We consider this a major limitation of our research. Different cultures might derive different characteristics in risk management. Data from different cultures can be employed in future studies for cross-cultural comparisons. Furthermore, others risks such as relation risk might be considered in the analysis to reach a more comprehensive view of the risks in CPD. Future research can move forward to examine the measures of risk management with the power asymmetry in CPD considered.

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Appendix

Questions on Risk Factors Identification

1. For the requirement construction, your company (team) has formed a regulated identification process, and the requirement can be recorded in standard files.

2. For each requirement acquisition, you and your experts will analyze the feasibility of this requirement together and then record the requirement description files.

3. If the requirement propositions are not complete, your team can detect them quickly and correct them by yourselves.

4. During the collaborative process, your team can deliver the function requirements to the designers of the supplier clearly and accurately.

5. The supplier's design team can understand your requirement description accurately.

6. A supplier records the requirement that you delivered and reviews the details of these requirement specifications with you many times.

7. After you have described your requirements to the supplier, it would analyze the feasibility of this

requirement specification and would note the infeasible parts if possible.

8. An information system serves the requirement management and has been constructed between you and supplier, and both of you can use the system proficiently.

9. If the requirement cannot be implemented by the supplier’s designers, you have to modify your designs to the level that can be met.

10. The technical strength of the supplier’s engineers can realize your requirement specifications.

11. The technologies adopted by the supplier’s engineers are a type of monopolized technology, provided only by them.

12. The supplier’s engineers can use the technologies proficiently and are not inexperienced.

13. The technologies adopted by the supplier’s engineers are mature rather than an unpopular novel technology or an obsolete technology.

14. The product designed by the supplier’s technology can be compatible with other products.

15. The resources of engineers and knowledge configuration on the supplier’s design team are adequate for the product design.

16. In the complex product development by the supplier and you, risks in the complex system are considerably higher than in a simple system.

17. It happens that the supplier promises to design some components initially; however, it cannot accomplish these goals when its design proceeds into an additional stage and if their technology is inadequate.

18. After a supplier delivers the design product to you, you may find that some functions have been missed because the requirement was incomplete in the initial phase.

19. After the supplier delivers the design product to you, you may find some product defects because the requirement was inaccurate in the initial phase.

20. The more iterations you have experienced, the closer the convergence to the design requirement specifications.

21. Sometimes, the supplier would neglect a few performance specifications to meet the deadline of delivery.

22. Your department would neglect a few unimportant performance specifications to meet the key nodes of critical paths.

23. During complex product development, your company has constructed a mechanism of verification

and validation, which can pinpoint the performance defects to the key nodes.

24. The more complex the product, the more difficult it is for the product's convergence to the performance specifications, in particular, the design of the product is full of interweaving actives.

25. It is highly probable that the schedule will be postponed if your requirement is incomplete or inaccurate.

26. During product development, there are many unintentional iterations, except for the intentional iterations.

27. The design plan is scientific because there is adequate time to accomplish the expected work among this interval.

28. Lack of sufficient communication and coordination between the supplier and you may cause schedule delays.

29. Delays might happen when one or more activities are missed at first and when these activities need to be redesigned later.

30. Delays might happen when the sequence for some activities are arranged incorrectly.

31. The more complex the activity coupling, the higher the probability of schedule risk occurrence.

32. If there are interfaces between your products and other products, then it is possible that the schedule delay in that product would affect your schedule.

33. It is more probable to have novel product development than mature product incremental development.

34. It is an ordinary phenomenon for your product design to experience a cost overrun than for it to be on budget.

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