Collaborative Product Development under Information Asymmetry

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Collaborative Product Development Under Information Asymmetry

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Abstract

Product design stage is utterly important for successful product development, as up to 90% of the product costs are locked in during the concept and design engineering phases. At these phases, manufacturers of new products actively involve their suppliers to participate in product development. However, academic literature has not given sufficient attention to the link between the early supplier involvement stage and the subsequent mass production stage. The goals of the product developing manufacturer and its suppliers are not necessarily aligned, which can result in serious inefficiencies. Therefore, the objective of this thesis is to resolve the conflict of incentives at the product design stage when a manufacturer of a new product involves a supplier of a key component. This thesis considers three important facets of collaborative product development: (1) multiple alternative designs of the key component, (2) parallel component development by several suppliers, and (3) testing of the key component by the supplier in order to learn its quality. Relying on the methodology of non-cooperative game theory, the thesis provides practical prescriptions on how to mitigate the incentive misalignment in each of the three cases.

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Introduction

Aujourd'hui, c'est de plus en plus fréquent que le produit nouveau est le résultat de la collaboration de plusieurs entreprises, le plus important, le fabricant du produit final et les fournisseurs de composants et de modules clés. Le processus de la conception de produits va irrépressiblement delà des limites d'une seule entreprise. Pour donner quelques exemples, tandis que pour le développement de Boeing-737 environ 35-50% de tous les composants ont été développés et par la suite achetés par les fournisseurs externes, ce nombre a atteint 70% pour Boeing-787 (Tang et al., 2009). Les futurs progrès de l'industrie du smartphone sont en grande partie liées aux nouveaux écrans de saphir ou écrans flexibles à haute résistance, qui sont en cours d'élaboration, non seulement par les fabricants de smartphones, mais souvent par les fournisseurs potentiels de ces écrans (*Solid State Technology*, 2014; Mone, 2013).

Le processus de la conception de produit comprend plusieurs étapes, de l'idée initiale à la production en série. Toutefois, jusqu'à 90% des coûts de production en série de produits sont verrouillés durant les premières phases d'ingénierie (Levin and Kalal, 2003), faisant ces étapes cruciales pour le succès du produit. Qu'est-ce qui se passe à ces étapes ? C'est exactement le moment où les entreprises impliquent leurs fournisseurs à participer à la conception de produits grâce au développement des composants clés pour le futur produit. Cependant, la littérature académique n'a pas accordé suffisamment d'attention à la collaboration avec les fournisseurs au stade de la conception initiale, en grande partie en se concentrant sur les étapes ultérieures de l'implication des fournisseurs. En particulier, le chaînon manquant adressée par cette thèse est la relation entre le stade de la conception initiale du composant clé et de son stade de la production en série, quand le fournisseur est impliqué et dans le développement de composants et son potentiel approvisionnement d'avenir.

Le problème profond de la conception collaborative de produits est que les incitations du fabricant du nouveau produit et le fournisseur du composant clé ne coïncident pas nécessairement. Par exemple, l'objectif du fabricant est souvent de maximiser la marge entre la valeur du nouveau produit et son coût de production en série, alors que l'objectif du fournisseur est d'assurer un contrat bénéfique pour la phase de production en série. En plus de cela, les pertes de réputation en cas de défaillance du nouveau produit peuvent être répartis de manière inégale. Il peut provoquer une distorsion supplémentaire dans incitations. Le problème peut être exacerbé par la distribution asymétrique des informations importantes. Le fournisseur est plus impliqué dans le développement de composants et il apprend forcément beaucoup plus sur la composante que le fabricant, qui, souvent, ne participe pas à la plus grande partie du processus de la conception, sauf pour la phase de test.

Comme le Schéma 1 représente, au moment de l'implication des fournisseurs les caractéristiques importantes du composante clé sont souvent inconnus. Les deux parties ont une estimation très approximative des coûts futurs de production en série et les avantages de ce composant, et même le fait de la faisabilité du composant peut être discutable. L'incertitude est aggravée encore davantage si plusieurs modèles alternatifs pour le composant existent. Toutefois, les contrats obligatoires de production en série sont signés à ce stade précoce, qui peut être

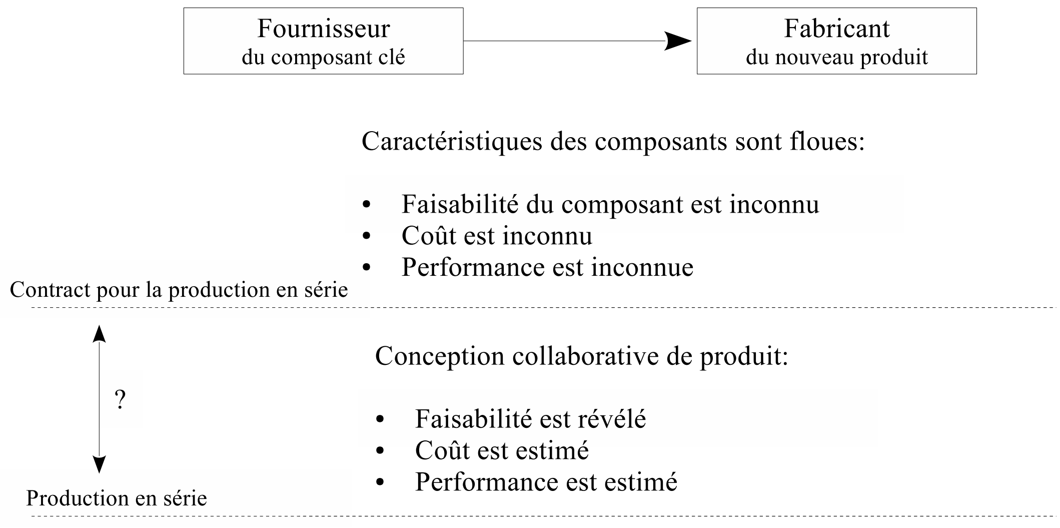


Schéma 1: Le processus d'implication des fournisseurs dans la conception de produit

longue avant l'étape de production en série. Après la signature du contrat, un certain nombre d'événements peut se produire : le fournisseur peut obtenir une meilleure estimation du coût futur du composant, certains modèles du composant peuvent être rejetées par l'une des parties, le fournisseur peut observer la qualité des composants, les équipes du fabricant travaillant sur le projet peuvent échouer ou réussir, etc. Le comportement du fournisseur et le fabricant à ce stade est largement définie par le type et les caractéristiques du contrat, qu'ils ont choisi. La relation entre le contrat pour la phase de production en série et le comportement des parties dans différents contextes de la conception de produit est l'objet d'étude de cette thèse.

Le désalignement d'incitation entre le fournisseur et le fabricant peut grandement fausser l'efficacité de la conception collaborative de produit. Par conséquent, l'objectif de cette thèse est de développer l'ensemble de recommandations de gestion, qui visent à atténuer les inconvénients de la conception collaborative de produit, tout en conservant tous les avantages de la collaboration. La conception de produit peut prendre de nombreuses formes différentes et impliquent donc différents problèmes potentiels. Trois de ces formes décrites ci-dessous sont pris en compte dans cette thèse.

La thèse se compose de trois essais chacune traitant d'un problème distinct dans le cadre général d'incitation conflits aux premiers stades de la conception de produit. Chaque essai constitue une base pour un article académique séparée avec la motivation, la revue de la littérature, et le modèle analytique indépendants. Néanmoins, chacun d'entre eux tentent de concilier les incitations de fabricant et fournisseur dans différents contextes de la conception de produit.

Dans le premier essai, nous étudions comment les approches classique de coût cible (coût-fondé et marché-fondé) doivent être ajustés en présence de designs alternatifs en raison de comportements opportunistes du fournisseur. Ayant acquis des informations privées sur les coûts de production en série du composant basé sur des designs différents, le fournisseur peut promouvoir certains modèles au détriment des autres, qui sont potentiellement plus bénéfique pour le fabricant. Par un moyen de soin réglage précis du contrat de coût cible, nous essayons de trouver un moyen d'atténuer le comportement opportuniste destructeur et accroître l'efficacité du processus de la conception collaborative. En présence de plusieurs designs alternatifs pour le même composant, il est important de répondre à une série de questions. Est un coût cible unique le meilleur choix pour obtenir le faible coût et le design de haute qualité ? Si le fabricant teste deux designs alternatifs, est-il possible de réduire les coûts encore plus par de fixer la cible basse pour la première, et une cible plus clémente pour la seconde ? Ces questions et d'autres, qui font face le fabricant, reçoivent l'attention primaire dans notre recherche.

Dans le deuxième essai, nous nous concentrons sur l'effet de la concurrence sur les efforts déployés par les fournisseurs au stade de la conception de produit. Pour atténuer l'incertitude inhérente au développement de produits, le fabricant du nouveau produit peut favoriser la concurrence interne et déployer plusieurs équipes de développement, travaillant en parallèle sur le même projet, mais essayant les approches et / ou designs différents. Le défi est de savoir comment choisir et répartir les fournisseurs pour les équipes internes concurrentes sous la condition que les fournisseurs ne partagent ont pas généralement les objectifs du fabricant et peuvent exercer différents efforts en fonction de la décision d'attribution de l'équipe. Nous considérons deux fournisseurs, chacun ayant une expertise en technologie différente, qui pourrait être potentiellement utilisé pour le développement de produits. Va l'attribution de plusieurs équipes à un fournisseur augmenter ou diminuer les efforts élevés par les fournisseurs concurrents ? La réponse à cette question définit largement la décision d'attribution de l'équipe optimale par le fabricant.

Le troisième essai est basé sur les nombreux exemples récents de défaillances des composants développés par des tierces parties. Sous la condition que le partage ex-post des coûts en cas de défaillance d'un composant est généralement compliquée en raison de divers obstacles juridiques et la potentielle faillite de la partie responsable, nous nous concentrons sur les contrats, qui inciterait les fournisseurs pour assurer la probabilité de réussite plus élevé pour leurs composants au stade de la conception. Nous considérons le fournisseur, qui peut exercer des tests coûteux pour apprendre la qualité des composants et ensuite décider de laisser aller le composant à la production en série ou l'abandonner. La stratégie alternative pour le fournisseur est pour laisser aller le composant à l'aveuglette, c'est à dire, sans des tests suffisants, pour la production en série. Nous nous concentrons sur deux contrats admissibles menant à différentes structures d'incitation : contrat de récompense, ce qui implique que le fournisseur reçoit un bonus en cas de succès du composant, et le contrat de récompense résiduelle, ce qui signifie que le fournisseur reçoit les résidus après que le fabricant conserve le bénéfice fixe prédéterminé. Techniquement, le dernier contrat implique non seulement récompenser en cas de succès, mais aussi des sanctions pécuniaires en cas de panne. En outre, nous construisons un contrat efficace qui coordonne le fournisseur et le fabricant et permet à la supply chaîne pour obtenir le meilleur résultat.

Conclusion

Cette thèse est une tentative pour apporter des solutions à certains des problèmes aigus, qui se produisent en raison de l'alignement des incitations entre le fournisseur du fournisseur d'un composant clé et le fabricant du nouveau produit aux premiers stades de développement collaboratif de produits. Nous avons examiné trois scénarios différents de collaboration et les problèmes correspondants, qui se posent dans son cours. Pour chaque scénario, nous avons construit un modèle analytique, qui comprend les spécificités de chaque cas particulier. En outre, par un moyen de la théorie des jeux non coopératifs, nous avons analysé les incitations des parties concernées et identifié les voies possibles, qui peuvent combler leurs objectifs.

Le premier essai traite de contrat de coût cible pour les designs différents du même composant, qui sont développés et testés séquentiellement. Comme le fournisseur acquiert des informations privées sur le coût de production en série de composants à base de différents designs, il peut manipuler le choix de la conception pour la phase de production en série de la manière opportuniste. Nous constatons que ce n'est pas nécessairement optimale pour régler les coûts cibles identiques pour les designs alternatifs similaires (en termes de coût des composants estimée et la performance au stade de la production en série), et il n'est pas nécessairement optimale pour régler différents coûts cibles pour les conceptions différentes. En outre, nous montrons que le calendrier des décisions est important, c'est à dire, pour régler les coûts cibles à l'avant (le régime avec engagement) ou pour annoncer chaque coût cible seulement avant un développement conception particulière (le régime flexible). Si, intuitivement le mécanisme de flexibilité peut être dominé, car il aggrave le comportement opportuniste du fournisseur, dans certaines circonstances, le fabricant peut effectivement profiter du comportement opportuniste du fournisseur en concevant soigneusement les coûts cible dans le régime flexible. Enfin, nous montrons qu'il est optimal pour tester les designs alternatifs dans l'ordre croissant de la marge bénéficiaire, si le coût des tests par le design est suffisamment faible, ce qui est en contraste avec la littérature, qui supprime l'effet du comportement opportuniste des fournisseurs.

Le deuxième essai aborde le problème des conflits d'incitation lorsque le fabricant crée plusieurs équipes parallèles travaillant sur le même projet. La décision cruciale pour le fabricant est d'allouer à chaque équipe de l'un des différents fournisseurs potentiels du composant clé de manière à ce que les fournisseurs exercent suffisamment d'efforts pour le développement de composants. On retrouve les niveaux de fournisseur d'équilibre de l'effort en fonction de l'allocation d'équipe entre les fournisseurs cadre de deux contrats admissibles: le coût cible et le performance-contingent contrat. Fait intéressant, nous constatons que le niveau d'effort espéré d'un fournisseur pourrait en fait augmenter, quand le nombre d'équipes travaillant avec le fournisseur augmente, si il y a des synergies entre les équipes. Cela signifie que l'augmentation de la concurrence (jusqu'à un niveau raisonnable) peut augmenter les niveaux de l'effort du fournisseur et, par conséquent, le bénéfice prévu par le fabricant. En outre, nous montrons que, même dans des situations, où un fournisseur domine l'autre dans les principales caractéristiques, il pourrait être optimale pour le fabricant d'allouer au moins une équipe au fournisseur pire à induire la concurrence et bénéficier des efforts des fournisseurs plus élevés.

Le troisième essai se concentre sur l'inadéquation des incitations à l'égard de tester le composant avant son adoption à l'étape de la production en série. Il existe de multiples exemples concrets, lorsque les fournisseurs n'effectuent pas suffisamment de tests et les fabricants manquent d'expertise à réaliser et identifier les tests nécessaires, qui pourraient résulter des défaillances des composants, après que le produit est développé et lancé. Nous étudions différents contrats admissibles entre le fabricant et le fournisseur et constatons, que ni contrat de récompense, ni contrat de récompense résiduelle ne peuvent pas atteindre le résultat optimal. La raison est que le fournisseur dispose de l'option de quitter le projet après la phase de test, qui rend le paiement résiduel non-applicable pour tous les résultats possibles. Étonnamment, bien que le contrat de récompense résiduelle conduit à très haut niveau de test par le fournisseur, il ne bénéficie pas le fabricant, parce que le fournisseur préfère ne pas laisser le composant moins qu'il est entièrement sûr dans sa fiabilité. En outre, nous construisons un contrat efficace menant au profit optimal de la supply chaîne. Cependant, cela implique des sanctions pour le fournisseur, même si il ne laisse pas le composant et choisit d'arrêter le développement, ce qui rend ce contrat difficile à appliquer dans la pratique. Par conséquent, nous concentrons notre attention sur l'analyse de la façon dont le fabricant choisit entre le contrat récompense et le contrat de récompense résiduelle. Enfin, nous étudions si les subventions du fabricant peuvent conduire à davantage de tests et dans quelles conditions le fournisseur aurait essayé d'améliorer le composant.

Dans l'ensemble, les idées principales de cette thèse peuvent être résumés comme suit:

- Le fabricant peut bénéficier à partir du comportement des fournisseurs opportuniste en ajustant soigneusement le coût cible. En particulier, si la différence de performance espérée de designs de composants alternatifs est suffisamment élevée et de leur rendement espéré est suffisamment supérieure à leur coût de production en série prévu, le fabricant doit déployer le régime flexible et commencer à tester les designs de composants avec un avec le rendement espéré inférieure.

- Concurrence supplémentaire entre les fournisseurs grâce à l'allocation plus des équipes internes peut stimuler les efforts de l'autre fournisseur et augmenter le bénéfice espéré du fabricant. Cet effet est valide, si le nombre total d'équipes est suffisamment petite et la synergie du fournisseur de travailler avec plusieurs équipes est suffisamment élevée. En outre, le fabricant peut trouver optimal d'allouer plus d'équipes au fournisseur, dont les capacités sont dominées par les capacités d'un autre fournisseur.

- Les contrats de récompense et de récompense résiduelle n'offrent pas suffisamment d'incitations pour le fournisseur pour effectuer les tests du composant au niveau optimal avant sa sortie pour la production en série. Pour inciter le fournisseur à effectuer les tests du composant suffisants, le fabricant peut avoir besoin de déployer un contrat de récompense résiduelle, qui pénalise le fournisseur, même si il choisit de ne pas laisser le composant pour la production en série.

Chapter 1

Introduction

1.1 Motivation

Nowadays, it is increasingly common that a new product is a result of collaboration of multiple companies, most importantly, the manufacturer of the final product and the suppliers of key components and modules. The product development process irrepressibly goes beyond the boundaries of a single company. To give a few examples, while for the development of the relatively old Boeing-737, about 35-50% of all components were developed and subsequently procured by the external suppliers, this number reached 70% for the recent Boeing-787 (Tang et al., 2009). The future advances in the smartphone industry are largely related to the new highly resistant sapphire or flexible displays, currently being developed not only by smartphone manufacturers but often by the potential suppliers of those displays (*Solid State Technology*, 2014; Mone, 2013).

Product development process incorporates multiple stages from the initial idea to mass production. However, up to 90% of the mass production costs are locked in during the concept and design engineering phases (Levin and Kalal, 2003) making these stages crucial for success of the product. What happens at these stages?

It is exactly the moment when companies involve their suppliers to participate in product development through the development of key components for the future product. However, academic literature has not given sufficient attention to collaboration with suppliers at the early design stage, largely focusing on later stages of supplier involvement. In particular, the missing link addressed by this thesis is the relationship between the early design stage of a key component and its mass production stage when a supplier is involved into both component development and its potential future procurement.

A deep problem of collaborative product development is that incentives of the manufacturer of a new product and the involved supplier of the key component do not necessarily coincide. For example, the manufacturer's objective is often to maximize the margin between the value of the new product and its mass production cost for the manufacturer, whereas the supplier's objective is to ensure a beneficial contract for the mass production stage. On top of that, reputation losses in case of a new product failure can be distributed unequally thus creating additional distortion in incentives. The problem may be exacerbated by asymmetric distribution of important information. The supplier, being more involved in the component development, inevitably learns much more about the component than the manufacturer who often does not participate in the component's development process except for the testing phase.

As Figure 1.1 illustrates, at the moment of supplier involvement the important characteristics of the component are often unknown. Both sides have a very rough estimation of the future mass production costs and benefits of this component, and even the very fact of component feasibility may be questionable. The uncertainty is aggravated even further if multiple alternative designs for the component exist. However, the binding mass production contracts are signed at this early stage which can be long before the mass production stage itself. After the contract is signed, a number of events can happen: the supplier can get a better estimation of

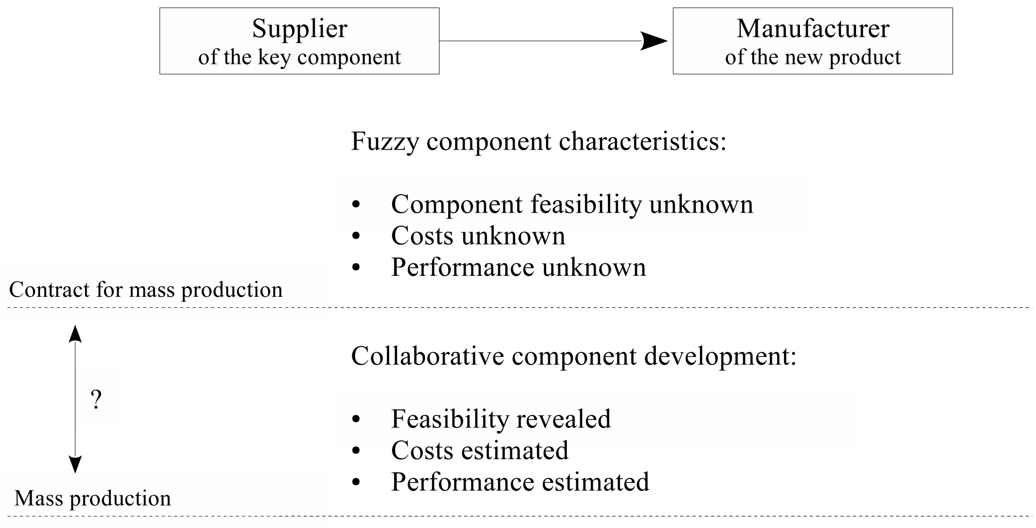


Figure 1.1: A Process View on Supplier Involvement in Product Development

the component future cost, some designs of the component can be rejected by either side, the supplier can observe the component quality, some of the manufacturer's teams working on the project can fail or succeed, etc. The behavior of the supplier and the manufacturer at this stage is largely defined by the type and characteristics of the contract they have chosen. The relationship between the contract for the mass production stage and the behavior of the parties in different settings of the product development is the cornerstone of the current thesis.

The incentive misalignment of the supplier and manufacturer can greatly distort the efficiency of collaborative product development. Hence, the objective of this thesis is to develop a set of managerial recommendations which aim at mitigating the disadvantages of collaborative product development, while keeping all the benefits of collaboration. Product development can take numerous various forms and therefore imply different potential problems. Three such forms described below are considered in the current thesis.

1.2 Thesis Structure

The thesis consists of three essays each dealing with a distinct problem under the general umbrella of incentive conflict at the early product development stages. Each essay forms a basis for a separate academic paper with independent motivational example, literature review, and analytical model. Nevertheless, all of them attempt to reconcile the manufacturer and supplier incentives albeit in different settings of the product development.

In the first essay, we study how the classical target costing approaches (cost- and market-based) need to be adjusted in the presence of alternative designs due to the supplier's opportunistic behavior. Having acquired private information about the mass production costs of component based on different designs, the supplier may promote certain designs at the expense of the others which are potentially more beneficial for the manufacturer. By a means of careful fine-tuning of the target costing contract, we try to find a way to mitigate the destructive opportunistic behavior and boost the efficiency of the collaborative development process. In the presence of multiple alternative designs for the same component, it is important to answer a series of questions. Is a single cost target the best choice to obtain a low cost and high quality design? If the manufacturer tests two alternative designs, is it possible to reduce the costs even more by setting an aggressive target for the first, and a more lenient target for the second? These and other questions facing the manufacturer receive the primary attention in our research.

In the second essay, our focus is on the effect of competition on the suppliers' efforts at the product development stage. To mitigate uncertainty inherent to product development, a manufacturer of a new product may promote internal competition and deploy several development teams working in parallel on the same project but trying different approaches and/or designs. The challenge is how to choose and allocate suppliers to the competing internal teams given that the suppliers do not generally share the manufacturer's objectives and can exert different efforts depending on the team allocation decision. We consider two suppliers, each with expertise in different technology that could be potentially used for the product development. Will allocation of more teams to a supplier lead to higher or lower efforts of the competing suppliers? The answer to this question largely defines the optimal team allocation decision of the manufacturer.

The research of the third essay is motivated by numerous recent examples of failures of components developed by third parties. Given that ex-post cost sharing in case of component failure is usually complicated due to various legal obstacles and the potential bankruptcy of the liable party, we focus on contracts which would incentivize suppliers to ensure a higher success probability for their components at the development stage. We consider a supplier that can exercise costly tests to learn the component quality and then decide to release the component for mass production or to scrap it. The alternative strategy for the supplier is to release the component blindly, i.e., without sufficient testing for mass production. We focus on two admissible contracts leading to different incentive structures: reward contract, implying that the supplier receives a bonus in case of component success, and residual claimant contract, meaning that the supplier receives the residuals after the manufacturer retains the predetermined fixed profit. Technically, the latter contract implies not only a reward in case of success but also monetary penalties in case of failure. Furthermore, we construct an efficient contract which coordinates the supplier and the manufacturer and allows the supply chain to achieve the first best outcome.

Chapter 2

Fine-Tuning Target Costing for Alternative Designs

2.1 Introduction

With competition growing fiercer, firms are forced to apply techniques to control and potentially reduce the costs of their products to stay competitive. A large percentage of these final product costs are determined during product development; an estimated 80% to 90% of the product costs are locked in during the concept and design engineering phases (Levin and Kalal, 2003). One widely-employed technique to achieve cost control during the development process is component-level target costing (Cooper and Slagmulder, 1999; Dekker and Smidt, 2003; Mihm, 2010). Component-level target costing has been used already in the 1960s by Japanese manufacturers (Feil et al., 2004), and is now widely applied by companies like Rolls-Royce (Zsidisin and Smith, 2005) and Mercedes-Benz (Albright and Davis, 1999). In component-level target costing, the manufacturer determines a target cost for a component before the component development takes place. While target costing can be applied both internally and with outside parties, component-level target costing is often discussed explicitly with suppliers in mind: "component-level target costing helps discipline and focus suppliers' creativity in ways beneficial to the buyer" (Cooper and Slagmulder, 1999, p. 24). Involving suppliers is critical, since suppliers account for as much as 50% of the product cost in the US (Ragatz et al., 1997), and due to increasing specialization suppliers are often responsible for designing the components they supply. Hence, design choices by suppliers determine a large part of the final manufacturing costs. The target cost provided to suppliers serves as a prominent reference point for the subsequent mass production contract price for the component (Monczka et al., 2008, p. 413).

Product development often involves choices about component designs; alternative designs, technologies or materials might be available, and the feasibility and final performance can only be determined in interaction with other components. For example, the supplier of floor beams for the Boeing-787, a subsidiary of Tata Motors, had first developed a prototype using Titanium, and, at Boeing's request, the supplier developed another prototype based on composite material. This beam development relied on cutting-edge technology, and only prototypes allowed Boeing and Tata Motors to estimate and compare the performance of both beam designs (Kulkarni, 2011).

The presence of alternative designs raises the question how target costs should be set. Is a single cost target the best choice to obtain a low cost and high quality design? If the manufacturer tests two alternative designs, is it possible to reduce the costs even more by setting an aggressive target for the first, and a more lenient target for the second? Or should the manufacturer rather start with a lenient target (to ensure development success at the expense of profitability), and use a more aggressive target for the second design? Should he even commit to the target cost level for the second design up front or should it be determined based on the outcome of the first design? For example, without commitment, if an aggressive target cost could not be achieved with the first design, the manufacturer could allow for a more lenient one for the second attempt, and otherwise, try again an aggressive target cost also for the second design. What is the impact of these choices on the incentives for the suppliers to provide the manufacturer with a functioning prototype? To the best of our knowledge, the existing literature on target costing seems largely silent regarding the above questions.

Indeed, the literature recognizes that the incentives of suppliers and manufacturers are largely misaligned, making suppliers focus more on achieving low component cost and manufacturers on developing a reliable component of high quality (Goldbach, 2002; Zsidisin and Ellram, 2003). In the presence of multiple design alternatives this problem is aggravated by information asymmetry: During the component design and testing, the supplier does not only learn about the components' performances but also obtains a better estimate of their respective mass production costs, which is not readily visible and verifiable for the manufacturer; (e.g., this was the case in the above example of Tata Motors and Boeing). Hence, the supplier might prefer a component design with lower mass production cost rather than with higher quality (if delivered at the same target cost), and she might resist a particular design by declaring it technically infeasible or infeasible at a given target cost level.

In this chapter, we focus on collaborative product development between a single supplier and a manufacturer, in which they jointly test different design alternatives. The literature on target costing proposes two fundamental approaches to determining target costs: A cost-based approach, where the target costs are derived from estimated purchasing and production costs for the component, and a market-based approach, where the target costs are derived from the value to the customer minus a desired profit margin (Kato, 1993; Ellram, 2000). We will therefore examine a setting with identical cost estimation (same distribution), but with performance estimates which are either the same for all design alternatives (functional components) or which differ (value-adding components). The cost-based approach would hence suggest identical target costs for the alternative designs, while the market-driven approach would suggest higher target costs for the designs with higher performance contribution. We build a game theory model to explore whether either of these approaches is appropriate for multiple design alternatives (and if so for which type of components). On top of this, we study whether the manufacturer should announce the target costs up front (commitment scheme), or he should keep the flexibility to adjust the target costs based on the outcome (flexible scheme). We do this by exploring the impact of the chosen approach on the supplier's incentives and behavior (whether or not she reveals a feasible prototype). We show that all three approaches, a single fixed target cost, different target costs committed to up front, and a flexible scheme allowing for adjustments of the target costs can be optimal but under different conditions. Overall, our study provides guidance to managers about fine-tuning the target costing approach for alternative designs.

2.2 Literature Review

This chapter contributes to different streams of literature. The literature on target costing is largely practitioner-oriented and builds on case studies or empirical data analyses. Ansari et al. (2006) provide a comprehensive literature review on this topic. The most important milestones for target costing in the context of product development are laid by Kato (1993) and Cooper and Slagmulder (1999) explaining its key principles, Tani (1995) and Davila and Wouters (2004) focusing on its benefits and drawbacks, and Ellram (2000, 2006) and Zsidisin and Ellram (2003) linking it to purchasing and supply chain management. Formal modeling approaches have not received substantial attention on this topic, with a notable exception of Mihm (2010) who compares target costing with other management practices focusing on incentives they create for product engineers. We contribute to the literature by identifying the ways to fine-tune target costing when a manufacturer interacts with the same supplier for multiple design alternatives, one of which will be chosen at the end of the design phase.

This chapter also contributes to the interface of the new product development and supply chain management literature. The new product development literature has largely focused on a single firm. Regarding design choice, the literature is typically modeled it as a search for the best alternative over a certain landscape of potential options. Key issues arising from this include the decision about sequential or parallel development, optimal number of tests to perform, and incorporation of learning in the testing strategy (Weitzman 1979, Loch et al. 2001, Dahan and Mendelson 2001, Erat and Kavadias 2008). Terwiesch and Loch (2004) have extended this literature by studying a collaborative prototyping process. Their model describes the prototyping for custom-designed products, where the supplier leads by setting the prices of the prototypes and the final product, and the customer mainly decides when to stop further search. In our model, it is the manufacturer (i.e., buyer) who leads the collaborative prototyping process by setting the designs' target costs and invites the supplier to develop (and de facto co-select) a design from a given set of alternatives. While our model is also a sequential collaborative prototyping model, this chapter focuses on a different trade-off than the above mentioned papers. Rather than focusing on the trade-off between performance and incurred prototyping costs (which we assume to be negligible in our mass production context), we focus on the incentives created for the supplier by the chosen design testing order and target costs.

From supply chain perspective, this chapter contributes to the recent research on information, incentive, and coordination issues in collaborative new product development (where the product is developed jointly by multiple entities interacting and communicating closely with each other). Bhaskaran and Krishnan (2009) focus on horizontal collaboration of two firms in the context of alliances and analyze the revenue, investment, and innovation sharing mechanisms between the participating firms. While extensively covering the sharing of product development cost, the authors leave the target costing for the mass production stage out of the scope of their analysis. Iyer et al. (2005) turn to vertical collaboration with hidden supplier capability. In their paper, the buyer decides on the amount of effort to exert to help the supplier develop the product, and their primary focus is on the development of the optimal screening contract through offering a menu of contracts. We suppress the analysis of the effort levels to concentrate on the dynamics stemming from the development of multiple prototypes. Kim and Netessine (2013) explore the possibility of new product cost reduction obtained through collaborative efforts exerted by both parties in the product development stage. Similar to our research, they consider the unit cost at the mass production stage. Their focus is however on incentives for optimal effort choices, while we explore incentive conflicts arising from inherent dynamics of the new product development process when one of multiple possible design alternatives has to be chosen prior to the product release.

2.3 Model

A manufacturer ("he") involves his supplier ("she") in the development of a new product component. The manufacturer has N distinctive designs and needs to choose at most one for mass production. We consider the scenario where prototype development consumes significant amount of resources (e.g., employees with relevant expertise and facility capacity), and therefore, the supplier develops distinctive designs one at a time. Such a sequential process is also assumed in existing studies, such as Thomke and Bell (2001), Erat and Kavadias (2008), and Terwiesch and Loch (2004). Formally, we assume that the prototyping process consists of N periods, indexed by $t = 1, \ldots, N$, and the supplier prototypes design t in period t. For each design t, the manufacturer sets a target cost, denoted by w_t. Note that although iterative cycles with small adjustments of the same design are possible within one period, the target cost remains fixed for these iterations. To study the optimal timing for setting w_t, we consider the following two schemes.

- Commitment scheme (C scheme). The manufacturer sets the target costs at the outset, (i.e., prior to period 1), and commits to making no adjustment. Namely, the manufacturer chooses a combination of $(w_1, w_2, \ldots, w_N)$. In a special case, the manufacturer can set equal target costs across the N designs, i.e., $w_1 = w_2 = \ldots = w_N$.
- Flexible scheme (F scheme). The manufacturer chooses the target w_t at the beginning of period t, so that he has the flexibility to adjust the target cost of design t after seeing the outcomes of the previous $t - 1$ prototypes.

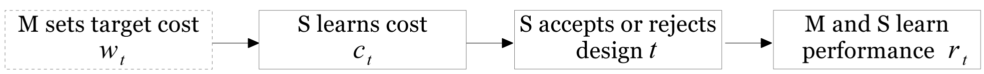
At the outset, the manufacturer chooses either the C scheme or the F scheme. In each following period t, through the prototyping process the supplier obtains an estimate of the mass production cost of design t, denoted by c_t. The supplier's cost estimation involves a lot of her private knowledge about past experience, manufacturing know-hows, technologies in development, tooling costs, second-tier suppliers, etc.; therefore, it is reasonable to assume that the cost c_t is the supplier's private information. However, we assume that both firms share the same estimation of the component cost, i.e., the distribution, prior to the development phase. This is reasonable because the manufacturer's "supply management [team] is working closely with the supplier in developing cost breakdowns, and gathering market data to assess the reasonableness of supplier cost estimates and determining what the costs 'should' reasonably be" (Ellram, 2006, p. 21). In particular, we assume that c_t is an independent draw from the probability distribution A with decreasing reversed hazard rate; commonly-used continuous or discrete distributions such as normal, uniform, exponential, geometric, binomial, Poisson, all satisfy this property (Block et al., 1998). Let $\overline{A}$ denote the tail distribution of A.

At the end of period t, the supplier releases prototype t for performance testing *only if* she accepts the target cost w_t; otherwise, she declares the design infeasible in the sense that it cannot be developed given the target cost w_t. In other words, we assume the manufacturer cannot force the supplier to release a prototype, nor will he renegotiate target costs (which goes against the purpose of target costing, since the option to renegotiate can induce the supplier to strategically hold the prototype and renegotiate for a higher target). We further discuss renegotiation in §2.7. If the supplier releases prototype t, the two firms jointly test prototype t and learn its performance, denoted by r_t. We note that such joint tests become increasingly common due to high-tech solutions for collaborative prototype testing (*Cisco*, 2010; Wijtkamp, 2012).

As in many studies on prototype testing, e.g., Terwiesch and Loch (2004) and Terwiesch and Xu (2008), we model r_t as a scalar. In particular, we assume r_t has binary outcomes 0 and $R_t > 0$, where 0 stands for zero payoff to the manufacturer in case design t fails the tests, and R_t is a deterministic payoff if design t passes the tests and is finally chosen. We assume that R_t is common knowledge due to the inherent nature of the target costing process in which "the purchasing organization must share anticipated sales and production schedules [with the supplier]" (Zsidisin and Ellram, 2003, p. 18). Formally, we assume that it is common knowledge that r_t is an independent draw from a two-point probability distribution G_t with probability mass $\alpha \in (0, 1)$ (i.e., success probability) on $r_t = R_t$ and with probability mass $1 - \alpha$ (i.e., failure probability) on $r_t = 0$.

We consider two types of components. When the component serves a simple and well-defined function, the manufacturer is indifferent to the choice between designs that perform to specifications, i.e., R_t equals some constant $R > 0$ for all t. We refer to such components as "functional components", reflecting their binary nature — the component based on a certain prototype either serves the required function or fails to do so, without any differentiation across successful prototypes. In other cases, however, different designs exhibit notable specification differences, for example, in terms of weight, volume, aesthetic attractiveness, etc. Each design, if successfully passing the tests, adds a considerably different value R_t to the manufacturer's final product. We refer to such components as "value-adding components". For example, a component made from composite material is expected to be lighter than a component made from metal, and thus the former may add a greater value to the final product if it works. Therefore, prior to prototyping both firms know the value of R_t. However, the feasibility of producing the component from either material is unknown.

Under both C and F target costing schemes, the target costs w_t are set prior to developing prototype t and thus remain independent of the realized performance value r_t. After all N periods, if all designs have been declared infeasible, the manufacturer uses the old design of the component (the outside option) and the two firms both receive normalized zero payoff; otherwise, the manufacturer chooses at most one feasible design for mass production. If the manufacturer chooses a feasible design t, his payoff is $r_t - w_t$ and the supplier's payoff is $w_t - c_t$. We assume both firms maximize their expected payoffs. This implies that the manufacturer will choose a design t such that $r_t - w_t \geq r_{t'} - w_{t'}, \ \forall \ t' \neq t$. In case of a tie between several designs, the manufacturer chooses one in accordance with the supplier's preference. Similarly, in case of indifference between accepting or rejecting a design, the supplier chooses to accept. Figure 2.1 presents the timeline of events.



Under the C scheme, the manufacturer defines all target costs in the beginning of period 1.

Figure 2.1: Event Timeline for Period t

In the next sections, we derive the firms' expected payoff functions and analyze their strategies in a subgame perfect equilibrium. In particular, we formulate the supplier's problem and characterize her strategy in §4; we need to introduce more simplifying assumptions in §5, where we formulate the manufacturer's problem, solve the equilibrium, and analyze the manufacturer's choice between C and F schemes. To examine the robustness of our results in §5 under more general (and hence complicated) settings, we extend our model and report numerical studies in §6.

2.4 Supplier's Optimal Strategy

In each period t, the supplier estimates the mass production cost of design t (i.e., observes c_t) and then chooses to either accept the target cost (and release the prototype for performance testing) or reject the design (by declaring the prototype infeasible). Her optimal decision depends on the target w_t and her cost estimation c_t. Furthermore, since her ultimate profit is determined by the manufacturer's final design choice, the optimal decision should be based on her evolving expectation about the manufacturer's final choice; under the C scheme, the decision should take into account the manufacturer's pre-chosen targets in the remaining periods $\{w_{t+1}, \ldots, w_N\}$, whereas under the F scheme the decision potentially affects those targets in the remaining periods.

To account for the various elements that can affect the supplier's sequential decision-making in N periods, we formulate her problem by a dynamic program. Define state variables π_t and v_t as the profits of the manufacturer and the supplier, respectively, if the manufacturer chooses the best among the successful designs in the first $t-1$ periods. We call the choice the status-quo and refer to π_t and v_t as the firms' status-quo profits; by assumption $\pi_1 = v_1 = 0$.

Suppose the manufacturer chooses a C scheme and announces $\{w_1, w_2, \ldots, w_N\}$ at the outset of period 1. In equation (2.1) we define the supplier's optimal profit-to-go function $u_t^C[\pi_t, v_t]$ under the C scheme at the time of the decision in period t:

$$u_t^C[\pi_t, v_t] = \max \begin{cases} u_{t+1}^C[\pi_t, v_t], & \text{if rejected;} \\ \Pr(r_t - w_t > \pi_t)\ u_{t+1}^C[r_t - w_t, w_t - c_t] & \\ + \Pr(r_t - w_t = \pi_t)\ u_{t+1}^C[\pi_t, (w_t - c_t) \vee v_t] & \\ + \Pr(r_t - w_t < \pi_t)\ u_{t+1}^C[\pi_t, v_t], & \text{if accepted.} \end{cases} \tag{2.1}$$

The right-hand side of equation (2.1) means that the supplier chooses to reject or accept design t by comparing her expected profits under the two scenarios. If she rejects the design, both firms' status-quo profits remain unchanged ($\pi_{t+1} = \pi_t$ and $v_{t+1} = v_t$) from period t to period $t+1$. By contrast, if she accepts the design, the state variables may change depending on the performance test result, i.e., the realized performance value r_t. In particular, if r_t is high enough, i.e., $r_t - w_t > \pi_t$, design t replaces the manufacturer's previous status-quo, and hence the new status-quo profits are $\pi_{t+1} = r_t - w_t$ and $v_{t+1} = w_t - c_t$; if r_t is too low, i.e., $r_t - w_t < \pi_t$, $\pi_{t+1} = \pi_t$ and $v_{t+1} = v_t$. Finally, in case design t ties with the manufacturer's previous status-quo choice, i.e., $r_t - w_t = \pi_t$, we assume the manufacturer chooses design t if it provides higher profits to the supplier. The sign $\vee$ means pairwise maximum.

Suppose the manufacturer chooses an F scheme. In such a case, the two firms engage in a sequential game. We consider the perfect Bayesian equilibrium. Since the manufacturer cannot observe the past costs, he updates his belief about v_t via Bayes' rule based on the supplier's decision to release or reject design t; we discuss the updating process in more details in the next section, where we formulate the manufacturer's problem. Let $W_t \equiv \{w_t, w_{t+1}, \ldots, w_N\}$ represent the manufacturer's strategy at the beginning of each period t. His strategy is a stochastic process of target costs in the remaining periods; in other words, the manufacturer's strategy, the supplier's decisions, and the updated belief together determine how W_t evolves. Using this notation, the supplier's optimal profit-to-go function under the F scheme at the time of the decision in period t is given by equation (2.2):

$$u_t^F[\pi_t, v_t |\, W_t] = \max \begin{cases} u_{t+1}^F[\pi_t, v_t |\, W_{t+1}^{(0)}], & \text{if rejected;} \\ \Pr(r_t - w_t > \pi_t)\ u_{t+1}^F[r_t - w_t, w_t - c_t |\, W_{t+1}^{(2)}] & \\ + \Pr(r_t - w_t = \pi_t)\ u_{t+1}^F[\pi_t, (w_t - c_t) \vee v_t |\, W_{t+1}^{(0) \text{ or } (2)}] & \\ + \Pr(r_t - w_t < \pi_t)\ u_{t+1}^F[\pi_t, v_t |\, W_{t+1}^{(1)}], & \text{if accepted.} \end{cases} \tag{2.2}$$

The superscripted $W_{t+1}^{(i)}$, $i = 0, 1, 2$, represent different possible paths of the stochastic process: subscript $i = 0$ for when the supplier rejects prototype t; $i = 1$ for when the supplier releases but the manufacturer rejects prototype t; last, $i = 2$ for when the supplier releases and the manufacturer accepts the prototype.

Equations (2.1) and (2.2) are defined for all $t = 1, ..., N$, subject to the terminal condition:

$$u_{N+1}^C[\pi_{N+1}, v_{N+1}] = u_{N+1}^F[\pi_{N+1}, v_{N+1} |\, W_{N+1}] = v_{N+1}, \quad \forall\, \pi_{N+1}, \forall\, W_{N+1}. \tag{2.3}$$

The supplier solves the dynamic program defined by (2.1) and (2.3) under the C scheme, or by (2.2) and (2.3) under the F scheme. Evidently, the solution depends on the manufacturer's strategy (which determines w_t and W_t) and the type of component (functional or value-adding, which determines the distribution of r_t). Therefore, one cannot fully characterize the solution in general. However, we prove some useful structural features of the supplier's optimal strategy, i.e., the best-response given the manufacturer's strategy, in Proposition 2.2. To build intuition, we first discuss some properties of the supplier's optimal profit-to-go function. We provide all the proofs in the Appendix.

Lemma 2.1. *The supplier's optimal profit-to-go function has the following properties:*

(i) Both $u_t^C[\pi_t, v_t]$ and $u_t^F[\pi_t, v_t|W_t]$ are increasing in v_t;

(ii) $u_{t+1}^C[\pi_t, v_t]$ is invariant to π_t if $R_1 - w_1 \leq R_2 - w_2 \leq ... \leq R_N - w_N$, and non-increasing in π_t, otherwise.

Lemma 2.1(i) means that the supplier's expected final profit evaluated in any period can only be higher if she derives a higher profit from the manufacturer's status-quo choice. While intuitive, the result has an important implication: The supplier follows a threshold policy. Note that under either scheme, the supplier's expected profit increases in v_t and, therefore, decreases in c_t, if she accepts design t. This can be easily seen from the expression on the right-hand side of equations (2.1) and (2.2). Furthermore, c_t does not vary the supplier's expected profit in case the supplier rejects design t. Together, this implies that under either scheme there exists a unique cost threshold in each period such that the supplier always releases the prototype if c_t is below the threshold and, otherwise, she always rejects it. This result is stated formally in Proposition 2.2. Lemma 2.1(i) has another non-trivial implication: The supplier never allows v_{t+1} to be lower than v_t under the C scheme, since change in v_t does not affect W_t as it does under the F scheme. As we shall explain, this implication establishes the general results in Proposition 2.2 (i) and (ii).

Lemma 2.1(ii) describes the impact of π_t on the supplier's expected final payoff, and it reveals when and how the two firms' payoffs are related. In particular, it suggests that under the C scheme there exists a conflict between the two firms' payoffs: The supplier is typically worse off if the manufacturer derives higher profit from his status-quo choice. Intuitively, this is because a manufacturer with a better status-quo choice is less likely to switch to a different design in the remaining periods, which lowers the supplier's chance to obtain a higher profit than her status-quo profit. There exists one exception: If the manufacturer sets the testing order and target costs so that his potential profit from design t (i.e., $R_t - w_t$) increases in t, he will always choose the last feasible design released by the supplier, independently of π_t, and hence the supplier's profit-to-go function is invariant. We note that the lemma does not say anything about the monotonicity of $u_t^F[\pi_t, v_t|W_t]$ in π_t. The reason is that under the F scheme the supplier's strategy dynamically interacts with the manufacturer's strategy (reflected in the stochastic process W_t). In particular, any change in π_t affects W_t and the overall impact on u_t^F cannot be determined in general.

Proposition 2.2. *In period t, there exists a unique threshold $\bar{c}_t$ that depends on π_t and v_t. The supplier releases prototype t if and only if $c_t \leq \bar{c}_t$. In particular, $\bar{c}_N = w_N - v_N$; for $t < N$:*

(i) Under the C scheme, $\bar{c}_t < w_t - v_t$, if $\exists\ t' > t$ such that $R_t - w_t > R_{t'} - w_{t'} \geq \pi_t$ and $\Pr(c_{t'} \leq \bar{c}_{t'}) > 0$; otherwise, $\bar{c}_t = w_t - v_t$.

(ii) Under the F scheme, $\bar{c}_t < w_t - v_t$, if $\forall\ t' > t$ such that $R_t \geq R_{t'}$; otherwise, $\bar{c}_t$ can be greater than, equal to, or smaller than $w_t - v_t$.

On the surface, the existence of $\bar{c}_t$ seems intuitive: The supplier releases prototype t if and only if c_t is sufficiently low. The main point of Proposition 2.2 is, however, that the supplier's acceptance threshold $\bar{c}_t$ generally deviates from the target cost w_t. In particular, Proposition 2.2(i) says $\bar{c}_t \leq w_t - v_t$ always holds under the C scheme. This implies that, once there has been some feasible design (and hence $\pi_t > 0$ and $v_t > 0$), the supplier will reject all feasible designs t with $c_t \in (w_t - v_t, w_t)$. The supplier rejects such designs to avoid that the manufacturer switches his preference to design t, which would reduce the supplier's status-quo profit (because $v_{t+1} = w_t - c_t < v_t$) — as Lemma 2.1 implies, the supplier should not allow this to happen.

Furthermore, Proposition 2.2(i) suggests that, unless the manufacturer sets the target costs such that his potential profit from design t (i.e., $R_t - w_t$) increases in t, the threshold $\bar{c}_t$ is strictly lower than $w_t - v_t$, which means the supplier will even reject a design t with $c_t \in (\bar{c}_t, w_t - v_t)$ — a design that can make both the manufacturer and herself better off (in terms of π_t and v_t, respectively). We will refer to such supplier behavior as *strategic rejection.* The intuition for such behavior is the following: Lemma 2.1(ii) implies that the supplier is worse off if the manufacturer's status-quo profit increases, ceteris paribus; therefore, the supplier would rather forego a small improvement of her status-quo profit than increase the manufacturer's status-quote profit. In other words, by rejecting such designs she improves the chance that the manufacturer accepts a future design which is more profitable for her.

Proposition 2.2(ii) suggests that the supplier's strategic rejection behavior can also occur when the manufacturer uses the F scheme. In particular, it surely occurs if the manufacturer sequences the designs in decreasing order of expected performance (i.e., R_t decreasing in t) or if the component is functional (i.e., $R_t = R$ being constant). In such cases, we prove that the manufacturer always reduces the target cost as his status-quo profit increases; as a result, the supplier has incentive to reject the prototypes that can only slightly increase her status-quo profit.

However, Proposition 2.2(ii) also suggests that, when the manufacturer uses the F scheme for value-adding components, the supplier may use a threshold $\bar{c}_t > w_t - v_t$, which means that the supplier may release a design t with $c_t > w_t - v_t$. This is surprising because such a design can only reduce her status-quo profit given $w_t - c_t < v_t$. We will refer to such supplier behavior as *strategic acceptance.* As

Proposition 2.2(ii) indicates, strategic acceptance occurs only if the supplier expects some design t' in a later period with high performance expectation (i.e., $R_{t'} > R_t$). In such a case, the supplier's strategic acceptance can manipulate the manufacturer's belief about v_t and hence induce the manufacturer to choose high target cost $w_{t'}$. We further discuss strategic acceptance of value-adding components in §2.5.2.

In summary, the dynamic nature of equations (2.1) and (2.2), the stochastic factors c_t and r_t, and the complexity in the manufacturer's strategy together create an analytical difficulty to characterize the supplier's best-response strategy. Despite so, the results in Proposition 2.2 reveal many insights about the manufacturer's design of the target costing scheme. First, as the supplier maximizes her profit in the collaborative prototyping process, she tends to strategically influence the buyer's final design choice, and she does so through two types of strategic decisions: strategic rejection and strategic acceptance. Second, both the component type (functional vs. value-adding) and the target costing scheme type (commitment vs. flexibility) affect the supplier's strategic behavior. In particular, the commitment scheme helps the manufacturer preempt the supplier's strategic behavior (as long as he sets the testing order and target costs so that $R_t - w_t$ increases in t), whereas the flexible scheme generally provokes either type of strategic behavior. Third, in the functional component case, the testing and target cost order $R - w_t$ matters; in the value-adding component case, the testing order R_t matters. In the next section, we investigate how the manufacturer optimally decides the testing order, and further seek insights to the manufacturer's preference between the two types of target costing schemes.

2.5 Payment Scheme Comparison

In this section, we formulate the manufacturer's problem under the two schemes, and examine his choice for both component types.

When choosing the C scheme, the manufacturer sets a target cost for each design at the outset of period 1. If the component is of the value-adding type (i.e., R_t is different across t), he also decides on the sequence of the designs to prototype. We denote the decisions by $\boldsymbol{w}^C = (w_1, w_2, \ldots, w_N)$ and $\boldsymbol{R}^C = (R_1, R_2, \ldots, R_N)$. Given $\boldsymbol{w}^C$ and $\boldsymbol{R}^C$, the supplier solves her decision threshold $\bar{c}_t$ at the outset of period t per dynamic program (2.1) given the realized state (π_t, v_t). In other words, $\boldsymbol{w}^C$ and $\boldsymbol{R}^C$ define the stochastic process $\{\bar{c}_1, \bar{c}_2, \ldots, \bar{c}_N\}$, which evolvement is governed by the realizations of c_t and r_t. Therefore, the manufacturer chooses $\boldsymbol{w}^C$ and the sequence of $\boldsymbol{R}^C$ to maximize his expected payoff at the outset of period 1:

$$\sum_{i=1}^{N} \mathbb{E}\left\{(r_i - w_i)^+ A(\bar{c}_i) \sum_{s \subseteq S \setminus \{i\}} \Big[\prod_{j \in S \setminus \{i\} \setminus s} \overline{A}(\bar{c}_j) \prod_{j \in s} A(\bar{c}_j) \Pr(r_i - w_i \geq r_j - w_j) \Big] \right\}, \tag{2.4}$$

where $S = \{0, 1, ..., N\}$ and s denotes any subset of $S \setminus \{i\}$. We explain expression (2.4) in the Appendix, part A.7.1.

When choosing the F scheme, the manufacturer sequences the designs to prototype if the component is of value-adding type. He sets the target w_t at the outset of period t, knowing that equation (2.2) defines the supplier's acceptance threshold $\bar{c}_t$. However, he cannot solve program (2.2) to precisely find $\bar{c}_t$ because he cannot observe the state variable v_t, which equals $w_k - c_k$, where k denotes the manufacturer's status-quo choice. The manufacturer knows w_k, but not c_k; as a result, he forms a belief about the distribution of c_k and updates it from period to period. Let B_t denote the belief at the outset of period t; B_t is null before the manufacturer has a status-quo choice. We formulate his dynamic program by equation (2.5):

$$y_t^F[\pi_t, B_t] = \max_{w_t} \mathbb{E}\left\{\overline{A}(\bar{c}_t)\ y_{t+1}^F[\pi_t, B_{t+1}^{(0)}] + A(\bar{c}_t)\ y_{t+1}^F[\max\{r_t - w_t, \pi_t\}, B_{t+1}^{(1)\text{ or }(2)}]\right\}, \tag{2.5}$$

with $t = 1, ..., N$ and the terminal condition $y_{N+1}^F[\pi_{N+1}, B_{N+1}] = \pi_{N+1}, \forall\, \pi_{N+1}, \forall\, B_{N+1}$. We explain equation (2.5) and provide details on the manufacturer's belief updating mechanism in the Appendix, part A.7.2.

Formulations (2.4) and (2.5) explain why in general the manufacturer's problem is analytically intractable. Under the C scheme formulation, the intractability stems from the evolution of the stochastic process $\{\bar{c}_1, \bar{c}_2, \ldots, \bar{c}_N\}$ and the complexity of the objective function (2.4). Under the F scheme formulation, the intractability stems from the manufacturer's belief updating process and the involved equilibrium of two dynamic programs (i.e., (2.2) and (2.5)). In fact, the game under the F scheme is very similar to a dynamic bargaining game with persistent private information (e.g., Kennan 2001, Loginova and Taylor 2008) in the sense that the supplier possesses private information about c_k and hence v_t, which exhibit correlation across periods. Even in those recent developments, economists conclude that "[t]o obtain results it is necessary to make some strong simplifying assumptions" (Kennan 2001, p. 2). In fact, both Kennan (2001) and Loginova and Taylor (2008) assume two periods and that the dynamic private information variable follows a two-point distribution.

To shed light on the manufacturer's problem under both schemes and seek insights to his preference between the two schemes, we make similar assumptions and focus in the rest of this section on the case $N = 2$ and assume that A is a two-point distribution with probability mass $\beta \in (0, 1)$ at $c_t = 0$ and probability mass $1 - \beta$ at $c_t = 1$, where the value 1 represents the standardized upper bound of the cost. Given that we focus on design alternatives rather than on modifications of a design, a small N reflects the reality well. The two-point distribution of c_t helps restore tractability of the belief updating process about B_t. We return to our general formulations (2.4) and (2.5) for our numerical examinations in §2.6.2, where we consider continuous distributions of c_t and check the robustness of the insights derived from the simplifying assumptions.

In the following, we focus our analysis on the case with $R_t > 1$; namely, the manufacturer pursues a potential design only if it offers a sufficiently high profit potential. However, our analysis easily extends to the case of $R_t < 1$, which is in fact simpler, since the only profitable condition is $c_t = 0$.

2.5.1 Functional Components

When the component is of functional type, the two designs are ex-ante symmetric, and so the manufacturer does not have a sequence problem. If the manufacturer chooses to use the C scheme and announces (w_1, w_2), he can predict $\bar{c}_1$ and the distribution of $\bar{c}_2$ by solving the supplier's dynamic program (2.1); then, he can evaluate his payoff by plugging w_1, w_2, $\bar{c}_1$, and the distribution of $\bar{c}_2$ in to expression (2.4). We solve his optimization problem (relegating the details to the Appendix, part A.3.1), and summarize the result in Proposition 2.3(i).

If the manufacturer chooses the F scheme, the two firms play a sequential Bayesian game defined by $\{w_1; w_2^{(i)}, B_2^{(i)}, i = 0, 1, 2\}$ and $\{\bar{c}_1; \bar{c}_2^{(i)}, i = 0, 1, 2\}$, where index i differentiates three scenarios of period 2: $i = 0$ if the supplier does not release prototype 1 and hence $\pi_2 = v_2 = 0$; $i = 1$ if the supplier releases prototype 1 but the prototype fails the performance test and hence $\pi_2 = v_2 = 0$; and finally $i = 2$ if the supplier releases prototype 1 and it passes the test and hence $\pi_2 = R_1 - w_1$ and $v_2 = w_1 - c_1$. To form a perfect Bayesian equilibrium, at $t = 2$ for each $i = 0, 1, 2$, $\bar{c}_2^{(i)}$ should solve the supplier's program (2.2), and $w_2^{(i)}$ should solve the manufacturer's program (2.5) given $\bar{c}_2^{(i)}$ and $B_2^{(i)}$; at $t = 1$, $\bar{c}_1$ should solve the supplier's program (2.2) given the equilibrium implied stochastic process W_1, and w_1 should solve the manufacturer's program (2.5) given $\bar{c}_1$. Finally, the belief $B_2^{(0)}$ and $B_2^{(1)}$ are null, and $B_2^{(2)}$ is the posterior distribution of c_1 given that $c_1 < \bar{c}_1^{(2)}$. We solve the equilibrium (relegating the details to the Appendix, part A.3.1), and summarize the result in Proposition 2.3(ii). Let $\underline{R} \equiv \min\left\{\frac{1-\alpha+\alpha\beta(1-\beta)}{(1-\alpha)(1-\beta)}, \frac{2-\alpha}{(1-\beta)(2-\alpha(1+\beta))}\right\}$, $\overline{R} \equiv \max\left\{\frac{2-\alpha}{(1-\beta)(2-\alpha(1+\beta))}, \frac{1-\alpha(1-\beta(1-\beta))}{(1-\alpha)(1-\beta)}\right\}$, and $\underline{R}^F \equiv \frac{1}{1-\beta}$.

Proposition 2.3. *Suppose the component is of functional type.*

(i) If the manufacturer chooses the C scheme, it is optimal to set (w_1, w_2) equal to $(0,0)$ when $R < \underline{R}$; equal to $(\alpha\beta, 1)$ or $(1,0)$ when $\underline{R} \leq R < \overline{R}$; and equal to $(1,1)$ when $R \geq \overline{R}$.

(ii) If the manufacturer chooses the F scheme, it is optimal to set $w_1 = 0$ and $w_2^{(1)} = w_2^{(2)} = 0$ when $R < \underline{R}^F$; set $w_1 = \alpha\beta$, $w_2^{(0)} = w_2^{(1)} = 1$, and $w_2^{(2)} = \alpha\beta$ when $\underline{R}^F \leq R < \overline{R}$; and set $w_1 = 1 + \alpha\beta$, $w_2^{(0)} = w_2^{(1)} = 1$, and $w_2^{(2)} = \alpha\beta$ when $R \geq \overline{R}$.

(iii) The optimal C scheme weakly dominates the optimal F scheme.

Proposition 2.3 provides rich insights. First, parts (i) and (ii) show that the manufacturer's optimal target costs under both schemes share a similar structure, namely, the functional component's potential value R drives the optimal choice of target costs. Intuitively, the manufacturer trades off between low target cost and high probability of prototype release (by the supplier). When R is sufficiently low, the manufacturer chooses the former over the latter; in particular, he uses the lowest possible target cost in both periods ($w_1 = w_2 = 0$). By contrast, when R is sufficiently high, the manufacturer chooses the latter over the former; in particular, he sets high target costs in both periods. When R is medium, the manufacturer may seek a low target cost from the first prototype and maximize the release probability of the second prototype in case the first fails; in particular, the manufacturer finds it optimal to use the medium $w_1 = \alpha\beta$ to "bet" on the first prototype (in which case the supplier releases only if $c_1 = 0$) and use the high $w_2 = 1$ to "secure" the second prototype if the first fails (in which case the supplier releases regardless of c_2). Alternatively, the manufacturer can "secure" the first prototype using $w_1 = 1$ and leave very modest probability of acceptance for the second design with $w_2 = 0$ (which would be released only if $c_2 = 0$ and $c_1 = 1$).

Second, the manufacturer takes advantage of flexibility in the F scheme: Except when $R < \underline{R}^F$, he sets a high target cost for the second prototype if the first one fails (i.e., $w_2^{(0)} = w_2^{(1)} = 1$) so as to maximize the release probability of the second one, and he sets a low target for the second one if the first one succeeds (i.e., $w_2^{(2)} = \alpha\beta$) so as to seek the low cost from the second prototype.

Surprisingly, although the F scheme provides the flexibility to set the target cost of the second prototype based on the outcome of the first one, the manufacturer is better off by using the optimal C scheme than the optimal F scheme, as Proposition 2.3(iii) clearly suggests. To elaborate this finding, we compare Proposition 2.3(i) with 2.3(ii), and note that the two strategies differ when $\underline{R}^F \leq R < \underline{R}$ (and the optimal payment is $(0, 0)$ under the C scheme and $w_1 = \alpha\beta$, $w_2^{(0)} = w_2^{(1)} = 1$, and $w_2^{(2)} = \alpha\beta$ under the F scheme) and $R \geq \overline{R}$ (with the corresponding optimal payments of $(1, 1)$ and $w_1 = 1 + \alpha\beta$, $w_2^{(0)} = w_2^{(1)} = 1$, and $w_2^{(2)} = \alpha\beta$). The optimal C scheme strictly dominates the optimal F scheme in these two cases. This is because the F scheme induces the supplier's strategic rejection in the first period (i.e., $\overline{c}_1 < w_1$ per Proposition 2.2(ii)) and as a result the manufacturer has to use a higher w_1 in the optimal F scheme than in the optimal C scheme. In particular, when $\underline{R}^F \leq R < \underline{R}$, we can show that any $w_1 < \alpha\beta$ in the F scheme will induce the supplier to always reject the first prototype: She does so to force the manufacturer to set the high second period target cost $w_2 = 1$. By contrast, by using the C scheme, the manufacturer commits to $w_2 = 0$, which removes the supplier's incentive of rejecting the first prototype with $c_1 = 0$; thus, the optimal C scheme (with low $w_1 = 0$) sufficiently induces the release of the first prototype when $c_1 = 0$. Similarly, when $R \geq \overline{R}$, the optimal C scheme preempts the supplier's strategic rejection (i.e., $\bar{c}_1 = w_1 = 1$ per Proposition 2.2(i)), and hence the supplier always releases the first prototype. By contrast, if using the F scheme the manufacturer has to set $w_1 > 1$ to induce the supplier to always release the first prototype; otherwise, if he sets $w_1 = 1$, the supplier will strategically reject when $c_1 = 1$.

To summarize, when the component is of functional type, the manufacturer should always prefer commitment to flexibility because the supplier always exhibits strategic rejection behavior under the F scheme (per Proposition 2.2(ii)). Proposition 2.2(i) suggests that, when the component is of functional type, the C scheme preempts the strategic rejection unless w_2 is sufficiently higher than w_1. This explains why some intuitive C scheme policies with $w_1 < w_2$ are not optimal. For example, one might consider $(w_1 = 0, w_2 = 1)$ as a reasonable strategy because it allows the manufacturer to bet on the lowest possible cost from the first prototype and at the same time secure the second prototype release if the first one fails. However, we find that this strategy can never be optimal because it induces the supplier to always reject the first prototype in the hope of obtaining a higher payoff from the second. By contrast, the C scheme $(w_1 = 1, w_2 = 0)$ avoids such strategic rejection, and Proposition 2.3 suggests that it is one of the optimal strategies when $\underline{R} < R < \overline{R}$.

Our results for medium R demonstrate an interesting contrast to the conventional target costing approaches. Recall that both cost- and market-based approach would prescribe equal target costs for both designs. Nevertheless, we show that for multiple design alternatives, differentiated target costs might be better because they allow the manufacturer to mitigate the supplier's opportunistic behavior. Hence, our findings shed light on how to adjust the conventional target costing approaches.

2.5.2 Value-Adding Components

Suppose the component is of value-adding type and there are two designs, one with potential performance R_H and the other with potential performance $R_L < R_H$. The manufacturer needs to determine the prototyping sequence, either as $(R_1, R_2) = (R_H, R_L)$ or as $(R_1, R_2) = (R_L, R_H)$. For either sequence, we solve for the optimal C scheme target costs (w_1, w_2) and find the equilibrium $\{w_1; w_2^{(i)}, B_2^{(i)}, i = 0, 1, 2\}$ and $\{\bar{c}_1; \bar{c}_2^{(i)}, i = 0, 1, 2\}$ under the F scheme. The procedures are the same as those described in §2.5.1 for the functional component case. Under each scheme, we compare the manufacturer's optimal payoff under the two sequences to find the optimal sequence, relegating the technical details to the Appendix, part A.3.2. We introduce a definition and notations, and summarize the results in Proposition 2.4.

Definition. A set of designs $\{R_H, R_L\}$ is referred to as having high performance difference if $R_H - R_L \geq 1$, and is referred to as having low performance difference, otherwise.

Proposition 2.4. *Suppose the component is of value-adding type and let* $\overline{R}^L \equiv \frac{1-\alpha+\alpha\beta(1-\beta)}{(1-\alpha)(1-\beta)}$, $\overline{R}^H \equiv \frac{1-\alpha\beta(1-\beta)}{(1-\beta)(1-\alpha\beta)}$, *and* $\underline{R}^F \equiv \frac{1}{1-\beta}$.

(i) *If the set of designs has high performance difference,* $R_L \geq \underline{R}^F$, *and* $(1-\beta)R_H + (1-\alpha-\alpha\beta)R_L \geq 2-\alpha$, *the manufacturer finds it optimal to choose the F scheme, in which he sequences* $(R_1, R_2) = (R_L, R_H)$ *and uses* $w_1 = 1-\alpha$, $w_2^{(0)} = w_2^{(1)} = 1$, *and* $w_2^{(2)} = 2-\alpha$.

(ii) *Otherwise, the manufacturer finds it optimal to use the C scheme. In particular, when the designs have low performance difference, if* $R_L \geq \overline{R}^L$ *and* $(1-\alpha)(1-\beta)R_L + (1-\beta)(1+\alpha\beta)R_H \geq 2$, *he sequences* $(R_1, R_2) = (R_L, R_H)$ *and sets* $(w_1, w_2) = (1, 1)$*; otherwise, if* $R_L < \overline{R}^L$, *he sequences* $(R_1, R_2) = (R_H, R_L)$ *and sets* $(w_1, w_2) = (1, 0)$*; otherwise, he sequences* $(R_1, R_2) = (R_L, R_H)$ *and sets* $(w_1, w_2) = (0, 0)$. *When the designs have high performance difference, he*

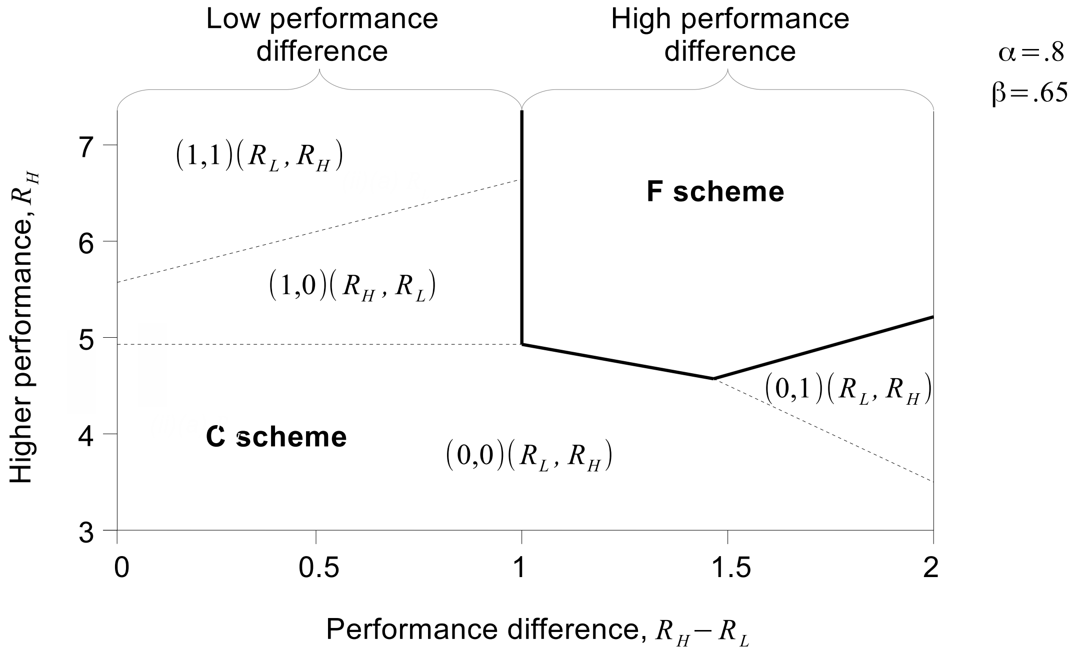


FIGURE 2.2: Optimal Target Costing Policy for Value-Adding Components

sequences $(R_1, R_2) = (R_L, R_H)$, *and he sets* $(w_1, w_2) = (0, 1)$ *if* $(1-\beta)(R_H - \alpha\beta R_L) \geq 1$, *and* $(w_1, w_2) = (0, 0)$ *otherwise.*

We illustrate the results of Proposition 2.4 in Figure 2.2, where the solid lines separate the two regions in which the manufacturer prefers different schemes (i.e., the optimal F scheme vs. the optimal C scheme), and the dotted lines separate the sub-regions in which the optimal C scheme implies different target costs. The most important result is Proposition 2.4(i), namely, the manufacturer can prefer the F scheme to all C scheme policies when the component is of value-adding type. This is in stark contrast to Proposition 2.3(iii), which suggests that the manufacturer should never use the F scheme when the component is of functional type.

When and why should the manufacturer prefer flexibility to commitment? Proposition 2.4(i) characterizes the conditions, namely, when both designs have high potential performance, i.e., $R_L \geq \frac{1}{1-\beta}$ and $(1-\beta)R_H + (1-\alpha(1+\beta))R_L \geq 2-\alpha$, and exhibit high performance difference, i.e., $R_H - R_L \geq 1$. Intuitively, when both designs have high potential performance, the manufacturer finds it optimal to maximize the release probabilities by setting $w_1 = w_2 = 1$ if he chooses to use the C scheme. However, even this optimal C scheme cannot induce the supplier to always release both designs: If he uses sequence (R_H, R_L) the supplier will strategically reject the first prototype when $c_1 = 1$; if he uses sequence (R_L, R_H) the supplier will not release the second prototype when the first is accepted and $c_1 = 0, c_2 = 1$, which is undesirable to the manufacturer when $R_H - 1 > R_L$. By contrast, by using the F scheme and sequence (R_L, R_H), the manufacturer can induce the supplier to always release the second prototype because he has the flexibility to set a very high target cost $w_2^{(2)} > 1$ (in case the first prototype was accepted) and set $w_2^{(0)} = w_2^{(1)} = 1$ (in cases the first prototype was rejected). Furthermore, the flexible second target cost creates an extra incentive for the supplier to release the first prototype because she expects the manufacturer to set $w_2^{(2)} > w_2^{(0)} = w_2^{(1)}$. This extra incentive is so strong that (under the conditions of Proposition 3) she chooses to always release the first prototype even if the manufacturer sets $w_1 = 1 - \alpha < 1$, which means that she accepts the first prototype at a loss when $c_1 = 1$. Hence, by carefully choosing the target costs the manufacturer can take advantage of the supplier's strategic behavior, as predicted by Proposition 2.2(ii). Corollary 2.5 summarizes this particular benefit of having the flexibility to set the target cost for the second prototype.

Corollary 2.5. *Under the conditions of Proposition 2.4(i), if the manufacturer uses the optimal F scheme, the supplier always accepts both designs, regardless of the realized costs c_1 and c_2.*

Nevertheless, if either R_H or R_L is insufficiently high, the manufacturer finds it too costly to induce the supplier to always release both prototypes; or if the second prototype does not provide sufficient improvement from the first one (i.e., $R_H - R_L < 1$, including the functional component case as an extreme case), the manufacturer is unwilling to set $w_2^{(2)} > 1$ after the first prototype was accepted. For those scenarios, he always prefers the C scheme, and this is consistent with the finding in Proposition 2.3(iii).

Proposition 2.4(ii) characterizes the optimal target costs when the manufacturer chooses the C scheme. The results are structurally similar to those for the functional component case (Proposition 2.3(i)). Now we compare them to the conventional target costing approaches. It is optimal to set high target costs $w_1 = w_2 = 1$ when both R_L and R_H are sufficiently high, and it is optimal to set low target costs $w_1 = w_2 = 0$ when both R_L and R_H are sufficiently low, which is consistent with the cost-based target costing. An interesting contrast occurs in the value-adding component case: One design has sufficiently high potential performance (i.e., $R_H > \overline{R}^H$) and the other has sufficiently low potential (i.e., $R_L < \overline{R}^L$). In such a situation, it is optimal to set a high target cost for the high-potential design and a low target cost for the low-potential design, which is consistent with the market-based target costing. Therefore, our results help delimit the applicability of cost-based and market-based target costing approaches.

Finally, Proposition 2.4 suggests that the manufacturer should strategically sequence the designs to avoid the supplier's strategic rejection behavior, i.e., to avoid the rejection of the first prototype when $c_1 = w_1$, per Proposition 2.2. We highlight this important finding in the following corollary.

Corollary 2.6. *In choosing the optimal target costs and scheme as prescribed by Proposition 2.4, it is weakly optimal for the manufacturer to sequence the designs in increasing performance order ($R_1 < R_2$) when using the optimal F scheme, and to sequence the designs in increasing payoff order ($R_1 - w_1 < R_2 - w_2$) when using the optimal C scheme.*

In other words, our analysis suggests that the manufacturer should always test the design with higher potential at a later stage, because such a sequence neutralizes the strategic rejection in the early period by assuring the supplier that he always chooses the last acceptable design. This finding could complement the well-known result in the sequential testing literature (Weitzman, 1979), which suggests that a single decision-maker should test designs in decreasing order of attractiveness (e.g., performance to cost ratio). The intuition to starting the test with the most attractive design is that the tester can stop the searching/testing as early as possible to save searching/testing costs. While we ignore the direct costs of testing, our results show that in collaborative settings this result might reverse. If both firms control the sequential testing process, a decreasing order of attractiveness induces strategic rejections by the supplier (Proposition 2.2), which can be more costly to the manufacturer than the cost of testing another design.

We can show that this result is robust even if we allow for (sufficiently low) direct testing costs. In particular, if

$$M \leq \begin{cases} \alpha(R_H - 1) - R_L, & \text{if } R_H < \underline{R}^F, \\ \alpha\beta R_H - R_L, & \text{if } R_H \geq \underline{R}^F, \end{cases} \tag{2.6}$$

where $M > 0$ is the manufacturer's cost of developing a prototype, the results on the optimal sequencing as formalized in Corollary 2.6 remain intact. The formal proof is provided in the Appendix, part A.6.1.

2.6 Robustness Tests

2.6.1 Parallel Prototyping

In the previous analysis, we have considered sequential prototyping process in which each design is released and tested after its development by the supplier. An interesting question is whether the manufacturer can be better off if the supplier can develop the designs in parallel or, equivalently, release all the prototypes at the same time. In this section, we compare the manufacturer's profit under the parallel prototyping to his profit under the sequential prototyping as considered in the previous section, and hence we continue to use the assumptions from §2.5. We find the following:

Proposition 2.7. *The optimal target costing policy under parallel prototyping is weakly dominated by the optimal C scheme policy under sequential prototyping.*

Proposition 2.7 states that the manufacturer should generally avoid parallel prototyping, even if prototypes are costless and the supplier has sufficient resources to perform the prototype development in parallel. The reason is that with parallel prototyping the supplier will learn the mass production cost for all designs, before her decision on which prototypes to release for testing. As a consequence, the manufacturer has to set higher target costs to ensure the same release probability as in the sequential prototyping case.

2.6.2 Multiple Prototypes

In §2.5, we focused on the two-design ($N = 2$) case and achieve analytical tractability by assuming the costs follow a two-point distribution. Our analysis yields the main insight to the manufacturer's choice of the optimal timing to set target costs: He should use the commitment scheme when the various designs have low performance difference (including the functional component case) and use the flexible scheme in the presence of high performance difference and sufficiently high performance relative to costs. The purpose of this section is to numerically examine the insight in the three-design cases ($N = 3$) where the costs follow two commonly used types of continuous distributions: normal and uniform.

Our numerical studies vary R_t (i.e., the designs' potential performance values) and the cost distribution parameters. We find that the main insight is robust. We provide a group of examples in Table 2.1, which reports the profit comparisons between the optimal C scheme and the optimal F scheme. In Table 2.1, the functional component case has two row sections: one assuming a normal cost distribution with mean 0.5 and standard deviation 0.1, i.e., $c_t \sim \mathcal{N}(0.5; 0.1)$, and the other assuming the standard uniform cost distribution, i.e., $c_t \sim U[0, 1]$. In each cost distribution section, we vary the performance value R from the mean cost 0.5 to 1.2. Similarly, the value-adding component case has the two cost distribution row sections. In each cost distribution case, we vary the set of performance values so that each next row has a higher maximum performance and a larger performance difference across designs. We report the manufacturer's expected profit (π_m), the supplier's expected profit (π_s), the supply chain's expected profit ($\pi_m + \pi_s$), and the optimal first-period target cost (w_1), under the optimal C scheme (columns C) and the optimal F scheme (columns F). To highlight the optimal scheme choice, we bold the values of π_m under the optimal scheme.

The examples of functional components confirm the main insight of Proposition 2.3, namely, the optimal C scheme weakly dominates the optimal F scheme, and the dominance becomes stronger as R increases because the optimal F scheme needs to use a higher first-period target w_1 than the optimal C scheme does. It is interesting to note that the optimal C scheme also makes the supplier and the supply chain better off.

The examples of value-adding components confirm the main insight of Proposition 2.4, namely, the manufacturer prefers the optimal F scheme when the performance difference across designs and the maximum performance design are sufficiently high. An important result (not reported directly in the table) is that the optimal testing sequence for value-adding components is in the order of increasing R_t in the optimal F scheme and in the order of increasing $R_t - w_t$ in the optimal C scheme. This confirms the results of Corollary 2.6 for $N = 3$ and more general cost functions.

Finally, we note that the strategic acceptance behavior exists in the value-adding

Condition	π_m		π_s		$\pi_m + \pi_s$		w_1	
$\alpha = .9$	C	F	C	F	C	F	C	F
Functional components								
$c_t \sim \mathcal{N}(0.5; 0.1)$								
$R = .5$	.04	.04	.04	.03	.08	.06	.42	.42
$R = .6$	**.09**	.08	.09	.06	.18	.14	.46	.46
$R = .8$	**.25**	.22	.24	.11	.48	.33	.52	.52
$R = 1.2$	**.61**	.56	.54	.16	1.15	.72	.56	.60
$c_t \sim U[0, 1]$								
$R = .5$	.13	.13	.10	.06	.23	.19	.22	.22
$R = .6$	.18	.18	.15	.08	.33	.26	.26	.28
$R = .8$	**.30**	.28	.25	.13	.55	.42	.34	.36
$R = 1.2$	**.58**	.52	.48	.26	1.06	.78	.44	.54
Value-adding components								
$c_t \sim \mathcal{N}(0.5; 0.1)$								
$R = \{.8, 1, 1.2\}$	**.51**	.50	.14	.13	.64	.62	.38	.36
$R = \{.8, 1.2, 1.6\}$	.83	.83	.12	.16	.95	.99	.30	.18
$R = \{.8, 1.2, 1.8\}$	.99	**1.01**	.16	.17	.64	.62	.30	.18
$R = \{.8, 1.2, 3.6\}$	2.57	**2.71**	.20	.30	2.77	3.01	.24	.02
$c_t \sim U[0, 1]$								
$R = \{.8, 1, 1.2\}$	**.46**	.44	.18	.22	.63	.66	.22	.32
$R = \{.8, 1.2, 1.6\}$	**.68**	.65	.27	.31	.95	.96	.22	.26
$R = \{.8, 1.2, 1.8\}$	**.79**	.76	.32	.38	1.11	1.15	.20	.32
$R = \{.8, 1.2, 3.6\}$	2.34	**2.44**	.43	.60	2.78	3.04	.02	.02

TABLE 2.1: Profit Comparisons between the Optimal C and F Schemes

component examples. When the performance difference is sufficiently high relative to the cost distribution mean and variance, the optimal F scheme sets a low first-period target. For example, consider the case $R = \{.8, 1.2, 1.8\}$ and the normal cost distribution: Here w_1 is as low as 0.18 under the optimal F scheme, and in comparison is $w_1 = 0.30$ under the optimal C scheme. The first-period target is so much lower under the optimal F scheme, because in equilibrium the supplier may strategically accept the first prototype at a loss to induce the manufacturer to set high targets for the next prototypes, in line with Proposition 2.2(ii).

2.7 Conclusion

Target costing has been suggested as a cost control mechanism that will allow firms to design products appropriate for today's competitive environment. In this chapter, we explore how target costing can be fine-tuned in a setting in which a firm explores multiple design alternatives with a supplier. While for each design target costs should remain non-negotiable to effectively control costs, multiple different designs raise the question how target costs should be set. In particular, are different approaches (cost-based versus market-based target costing, and commitment versus flexible schemes) appropriate for determining the target costs for different designs?

We show that in the presence of alternative designs a single target cost can result in opportunistic behavior by suppliers, who reject prototypes which would otherwise be profitable for both parties. Manufacturers can however adjust this opportunistic behavior by carefully choosing the target costs for multiple designs. Interesting, for designs with a-priori the same estimation of cost and performance (referred to as functional components), where both target costing approaches would prescribe the same target cost, the managers may optimally set different target cost levels to adjust the supplier's opportunistic behavior. On the other hand, for value adding components, higher performance designs do not necessarily need to be coupled with higher target costs (market-based determination of target costs), but a fixed target cost (cost-based determination of target costs) can be optimal. Even more interesting, if there are large differences between the designs' expected performances, the manufacturer can turn the suppliers' strategic behavior into an advantage by choosing a flexible scheme, where each target is set only after the results of the prior prototyping test are known. Hence, our results, summarized in Figure 2 above, provide guidance to managers how to adjust the target costing approach to the specific situation faced for a component.

Our study generates new insights to the problem of sequential prototype testing. To reduce the cost of testing, one would typically want to test designs in decreasing order of performance contributions (given identical costs). While our scenario is very different in the sense that we do not focus on when to stop testing (both designs will be tested), our results have nevertheless interesting implications and suggest that determining the optimal sequence of testing is more complicated whenever prototypes are developed with suppliers. With small enough costs of prototyping (to the manufacturer) we find that it is beneficial to test designs in increasing order of performance contributions, in order to reduce the supplier's strategic behavior, a factor that could also play a critical role and turn around the results in scenarios where manufacturers can decide when to stop testing. Our results also shed new light on the choice of parallel versus sequential prototyping. Intuitively, parallel prototyping is a more appropriate form of testing the designs (e.g., to speed up time to market), if the prototyping costs are negligible. However, parallel testing can give rise to even more strategic behavior by the supplier. Hence, even if parallel prototyping is feasible (i.e., there is no capacity constraint on the development side for suppliers), doing so might not be in the interest of the manufacturer, if time to market pressures are not too high. Taken together, these findings suggest that we need to be careful about making target costing and prototyping decisions whenever suppliers are involved.

We now discuss some limitations of our current model and potential future research. Our model largely assumes negligible testing costs, and hence is appropriate for the scenarios where the manufacturer has already decided to test two (or a few) design alternatives before making a choice among them. If the testing costs are significantly high or if many alternative designs exist, manufacturers need not to test all designs and might prefer stopping the search for a good component based on observed performances, which points to an interesting avenue for future research. Our model assumes no learning between designs (similar to the early testing literature), which well captures the scenarios when the manufacturer wants to test a few very different designs. Another avenue for future research is hence to incorporate learning in our model, similar to what Erat and Kavadias (2008) have done for the single-firm prototyping scenario.

Chapter 3

Effect of Supplier Competition on Parallel Team Deployment

3.1 Introduction

In this chapter, we examine the effect of competition between the suppliers involved in the development process on the conventional product development practices. In particular, we focus on the creation of parallel teams, i.e., the creation of several internal development groups aimed at developing the same new product. The rationale behind forming the parallel teams is the desire to manage uncertainty — different teams will choose different paths and/or technologies for the new product development, and hence the probability of the development success increases. The reason for parallel rather than sequential teams is mainly linked to the today's requirement for quick time to market, which can be achieved by following the parallel approach.

Due to increasing technological complexity, product development teams are rarely capable of developing the new products totally in-house. As we have seen in Chapter 2, it is more and more common that external parties, typically future suppliers, develop key components for the new products. This adds a new layer of complexity to the problem of parallel team deployment.

The suppliers as external parties may have different objectives from the manufacturer of the new product. In case of parallel teams, the manufacturer's objective is to ensure that at least one team succeeds with product development whereas the resulting product is of high quality and/or reasonable costs. For a supplier, the difference is that her objective is to ensure that at least one team, among those with which she works, is chosen by the manufacturer for the mass production stage. In other words, the suppliers are not interested in maximizing the component performance or minimizing its cost as a primary objective, but rather they seek to outperform the competing suppliers.

Being a complex process, product development implies significant non-contractable efforts necessary for the successful completion of the development and for achieving a high level of performance. From the suppliers' side, these efforts reflect the amount of resources allocated to the development project in general — the supplier may choose to prioritize this project over her other projects, search for better second-tier suppliers, allocate her best personnel to this project, etc. Monitoring of all these various project-related efforts can be very costly if not infeasible, and hence the corresponding specifications are rarely included in the contracts. Therefore, the manufacturer needs to ensure that the supplier has sufficient incentive to exert high efforts, i.e., to find the best second-tier suppliers, provide the best possible amenities to the manufacturer's teams at the expense of her other projects, etc.

In the light of the above, it is vital for the manufacturer to understand how competition affects the supplier incentives. Does allocation of more teams to a supplier lead to higher or lower efforts from her side? How does it affect efforts of another supplier? The answer to these questions is far from being intuitive. For example, when supplier A receives more teams to work with, supplier B faces a clear trade-off. On the one hand, the chances to succeed diminish for supplier B and therefore she might prefer lower effort level, but on the other hand, supplier A empowered with more teams may also reduce her effort prompting supplier B to try to outperform her. This problem has an important application for the allocation of teams to different suppliers. The manufacturer can allocate his teams to two alternative suppliers, while one supplier is clearly better than another, i.e., one supplier will definitely develop a higher performing component than another given the same effort levels from their sides. Is it optimal for the manufacturer to allocate a high number of teams to the better supplier, or on the contrary, allocate them to the worse supplier to put more pressure on the better one?

In addition to different expertise levels, the suppliers can work with different technologies making the team allocation decision even more difficult. For the development of the Dreamliner, Boeing has involved the supplier of lithium-ion batteries, a technology never used before in aviation industry (LeVine, 2013). Although the probability of success for a new technology is clearly lower than for a conventional technology, in case of success the performance will be greater given the same efforts from the supplier. Does it mean that the manufacturer should optimally allocate more teams to the more risky but highly promising technology or the reverse?

3.2 Literature Review

The research on parallel new product development originates from Nelson (1961) who considers the optimal number of teams developing alternative designs with the objective to choose one team whose design promises the lowest cost for the final product at a predetermined review time. Abernathy and Rosenbloom (1969) discuss the application of parallel strategy as an efficient way to deal with high uncertainty. Arditti and Levy (1980) further develop this idea for the case when design performance is stochastic and focus on the trade-off between the cost of maintaining parallel teams and the increase in the overall project success probability.

Tandon (1983) considers the environment, in which multiple firms decide to undertake competing R&D projects, and his focus is on the number of firms which will enter the competition. In his model, the decision on number of parallel projects is decentralized and depends on the environment parameters. This approach but with environment defined by another party rather than by nature is further developed within the literature on open innovation tournaments (see, for example, Terwiesch and Xu 2008 and Terwiesch and Ulrich 2009). The main difference of our research is that it focuses on the problem of supplier allocation to parallel teams, and the suppliers are heterogeneous in their capabilities.

One can draw a parallel between our work and Erat and Krishnan (2012) where agents are (self-)assigned to different solution areas. However, the prominent difference is that the solution areas cannot decide on their effort level opposite to the suppliers. Erat and Krishnan (2012) conclude that it is beneficial to explore less promising supplier area to increase the breadth of search, so that if a more promising solution area fails, a less promising can succeed. In our model, we capture an additional effect of supplier competition, and we find that it might be beneficial to work with less capable suppliers, even when we suppress the benefit of the breadth of search.

Another research stream focuses on internal team motivation and inter-team collaboration, the issues raised by Birkinshaw (2001). Taylor (2010) provides an insightful case analysis discussing the strategies of team collaboration. Sundaresan and Zhang (2012) investigate the optimal incentive schemes for collaborative and non-collaborative parallel teams. Our research has a different focus on investigating the incentives of the third parties, key component suppliers, rather than the incentives of internal teams.

Ding and Eliashberg (2002) consider new product as a sequential process and analyze the optimal number of parallel teams (approaches) in different stages of the process, thus optimizing the overall development pipeline. In our research, we focus on a particular stage of the new product development when external suppliers need to be involved to create viable prototypes based on different parallel approaches. By concentrating on a particular stage, we are able to describe the rich interaction structure of incentives of internal and external parties.

The comparison of parallel strategy to sequential has received a vivid coverage in the literature. Morgan and Manning (1985) show the benefits of the hybrid parallel/sequential strategy. Dahan and Mendelson (2001) provide the analysis of different strategies under different extreme-values distributions. The learning dimension is incorporated by Loch et al. (2001).

Another problem related to our research is how to allocate limited resources between parallel projects or teams. Gerchak (1998) addresses this issue under different objectives of the focal company. Gurler et al. (2000) establishes the conditions for the closed-form solutions. However, the underlying incentive conflict is far from one between a manufacturer and an external supplier.

Our research can be also described in the formal language of principal-agent model. The principal hires two different class of agents, development teams and suppliers, and finds the optimal matching between the agent types with the objective to maximize the probability of the development success. The problem is, however, different from the classical matching problem (as described by Mortensen 1982) as the buyer can directly allocate each team to a particular supplier. Our focus is not on the partner choice but rather on the game between suppliers once the allocation is externally set.

3.3 Model

For the development of a new product, the manufacturer of the new product creates m parallel teams, which he can allocate to different suppliers. We treat the number of parallel teams as an exogenous variable since it is often defined by the disposable budget or resources for the project. Our primary focus is thus on how to optimally allocate the teams. Capturing the trade-off between the new and conventional technologies, we consider two asymmetric suppliers: supplier n who has higher expertise for working with the new technology and supplier c whose expertise lies in the domain of the conventional technology.

In our model, we allow for two sources of uncertainty. The first is the technology uncertainty — a technology might prove to be unsuitable for the new product despite any supplier efforts and the number of teams allocated to the supplier. The new and conventional technology prove to be feasible for the new product with probabilities γ_n and γ_c, respectively, so that $\gamma_c > \gamma_n$ to reflect the intuition that conventional technology might work for the new product with higher probability than new technology. The second uncertainty source stems from the team level; each team can succeed with probability α.

Each supplier decides on how much efforts, e_n^j and e_c^j, to exert toward each team j allocated to her. The efforts are costly, and we assume a continuous and twice differentiable cost function $c(e_i^j)$ for $i = n, c$ and $j = 1, 2, ..., t_i$ such that $c'(e_i^j) > 0$ and $c''(e_i^j) \geq 0$, where t_i is the number of teams allocated to supplier i. The total cost the supplier bears for all the teams allocated to her we describe as $c(e_i)(1 + \beta(t_i - 1))$ where $\beta \in [0, 1]$ is the level of component customization, which defines the supplier's synergy of efforts. If $\beta = 1$, the component is fully customized for each team, and thus the supplier does not enjoy any potential synergy, while on the other extreme with $\beta = 0$ additional teams do not lead to any extra costs.

We assume that the teams are ex-ante symmetric, and the suppliers exert the same effort level toward each of the teams allocated to her. Although it might be different for the projects with multitudinous parallel teams, generally a supplier is expected to work with no more than 2 or 3 teams, and any unjustified preferences toward some teams from the supplier's side would promptly become evident for all parties raising the reputation concerns.

Supplier efforts define the component performance $r_i(e_i)$ for $i = n, c$. In line with the existing literature, we define performance as a single-dimensional measure. We assume that performance increases in efforts but with a diminishing marginal return, i.e., $r'(e_i) > 0$ and $r''(e_i) \leq 0$. Furthermore, let $r_n(e) \geq r_c(e)$ for a given effort level to reflect the advantage of the new technology. We consider performance deterministic, however, our insights are robust for the stochastic setting under the risk-neutrality assumption. The model captures the performance risk through probabilities of their success, γ_n and γ_c. We assume that both parties are risk neutral, as in practice a large supplier involved in component development is typically no more risk averse than a manufacturer.

Graphically, Figure 3.1(a) presents the supply chain at the product development stage, and Figure 3.1(b) describes the event sequence in our model. First, the manufacturer allocates t_n teams to the new technology supplier and t_c teams to the conventional technology supplier so that $t_n + t_c = m$. All teams are considered ex-ante symmetric in our model. Then the suppliers simultaneously choose effort levels e_n and e_c. Finally, the uncertainty on the technology and the team levels is resolved, and the manufacturer chooses for the mass production the supplier with higher performance $r_i(e_i), i = n, c$ providing the technology of the winning supplier and at least one team succeeded.

To simplify the notation, we will denote the probabilities that a supplier succeeds in the development with at least one team as $S_n \equiv \gamma_n\Big(1 - (1 - \alpha)^{t_n}\Big)$ and $S_c \equiv$

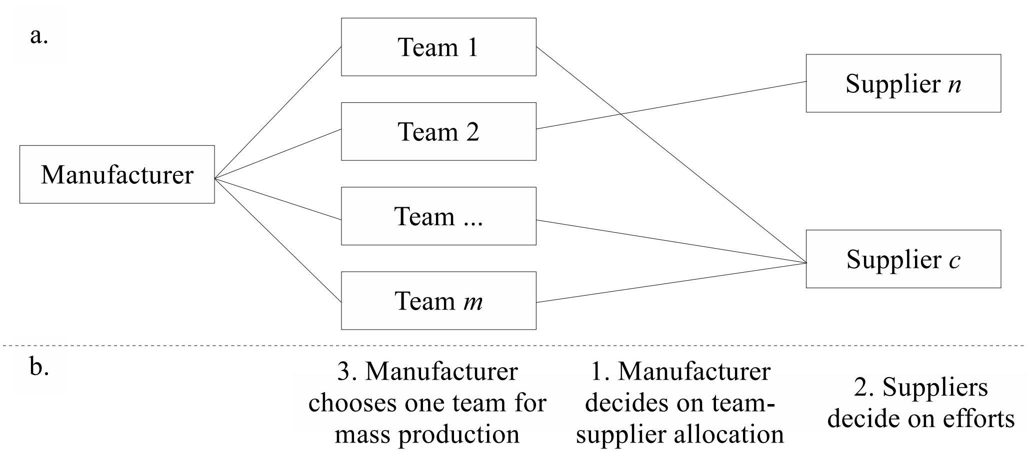


FIGURE 3.1: (a) A Typical Supply Chain at the Product Development Stage and (b) Event Sequence

$\gamma_c\Big(1-(1-\alpha)^{t_c}\Big)$, and the supplier's costs as $B_i \equiv 1+\beta(t_i-1)$, where $i=n,c$.

We will consider two contracting schemes for the new product development: target costing and performance-contingent reward. Under the target costing scheme, the manufacturer sets the target for the price of the component at the mass production stage, and this price is independent of the component performance. Generally, this approach leads to better cost control from the manufacturer's side, but it might shift the supplier's objective away from maximizing the component performance. Performance-contingent reward implies that the supplier receives a pre-defined portion of the component performance as the price at the mass production stage.

3.4 Target Costing Incentive

Before diving into the formal definition of equilibrium efforts, let us discuss the intuition behind the supplier's behavior. Consider Figure 3.2 comprising of two graphs: performance as a function of efforts on top and cost as a function of efforts below. After the manufacturer announces the target cost u, the suppliers need to ensure that their components perform above this level (to satisfy the manufacturer's participation constraint), and $\underline{e}_n$ and $\underline{e}_c$ denote these minimum effort levels for the new and conventional technology supplier, respectively. On the lower graph, we can see the costs $c(\underline{e}_n)$ and $c(\underline{e}_c)$ incurred by each supplier.

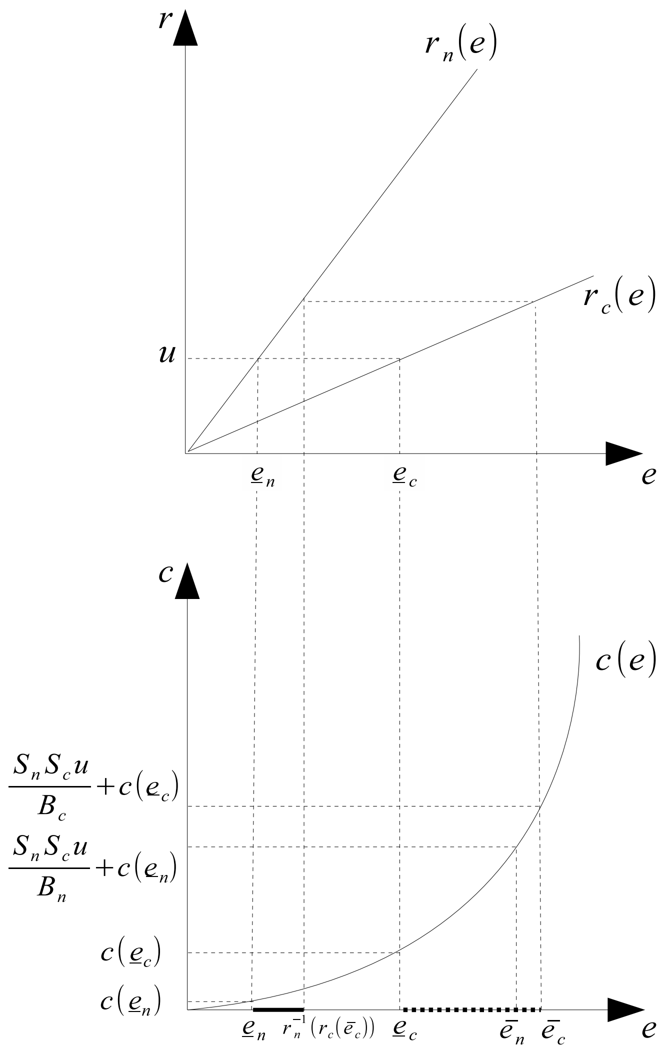


Figure 3.2: Supplier's Efforts under Target Costing Contract

Note that if any of the suppliers exerted a slightly higher effort, her component performance would be higher and therefore she will be chosen by the manufacturer. Each supplier would prefer to increase her efforts until the point when costs of efforts outweigh the benefit of having a higher performing component. From the analysis of supplier payoff as we will further discuss in Equation (3.1), we find that this point is achieved when the cost equals $\frac{S_n S_c u}{B_i} + c(\underline{e}_i)$, for $i = n, c$. We denote the corresponding maximum effort levels as $\bar{e}_n$ and $\bar{e}_c$. However, supplier n can achieve the performance of $r_c(\bar{e}_c)$ at a lower effort level than $\bar{e}_n$. Since $r_n^{-1}(\bar{e}_c) < \bar{e}_n$, supplier n would never exert any effort above $r_n^{-1}(\bar{e}_c)$ in equilibrium, as the other supplier never finds it beneficial to exert effort leading to a higher performance.

Therefore, in equilibrium supplier n can exert efforts in the interval $[\underline{e}_n, r_n^{-1}(\bar{e}_c)]$ and supplier c — $[\underline{e}_c, \bar{e}_c]$. Note that $\bar{e}_c$ defines the maximum equilibrium effort for both suppliers, whereas $\bar{e}_n$ does not play a role. Recall that $\bar{e}_c = \frac{S_n S_c u}{B_c} + c(\underline{e}_c)$. Considering $\frac{S_n S_c u}{B_c}$, we can see that it is non-monotone in t_c and monotone in t_n. In practice it means that sometimes adding more teams for the conventional technology supplier may result in higher efforts exerted by the new technology supplier. In the remainder of the section, we formalize the analysis and identify the conditions when this property holds.

We start with formulating the suppliers' objective functions which are discrete because each supplier can be either the first or the second best choice for the manufacturer depending on the exerted efforts. Note that $v_i(e_i)$ stands for *expected* profit of supplier i since the technology and team uncertainty is incorporated through γ_i and α, respectively, where $i = n, c$.

$$v_i(e_i) = \begin{cases} \begin{cases} S_i u - c(e_i)B_i, & \text{if } r_i(e_i) > r_j(e_j); \\ S_i(1 - S_j)u - c(e_i)B_i, & \text{if } r_i(e_i) < r_j(e_j); \end{cases}, & \text{if } r_i(e_i) \geq u; \\ 0, & \text{if } r_i(e_i) < u. \end{cases} \tag{3.1}$$

where $i \neq j$ and $i, j = n, c$. The probability that supplier i succeeds with at least one team is S_i. However, if she is the second-best choice for the manufacturer, she also needs that the other supplier fails, which happens with probability $1 - S_j$. In any case, each supplier bears cost of effort proportional to the number of teams allocated to the supplier and corrected on the synergy level across teams. For simplicity, we do not allow for a tie between suppliers but all the results hold true if we consider ties with random tie break mechanism. The intuition is that each supplier can easily break the tie in her favor by exerting an ϵ higher effort, where ϵ is a small positive value.

For the equilibrium analysis, we limit our attention to the case when a supplier chooses to participate even when she is the second best choice, i.e., $c\left(r_i^{-1}(u)\right) \leq \frac{S_i(1-S_j)u}{B_i}$. The analysis for the opposite case follows similar logic.

Proposition 3.1. *Under the target costing reward,*

i. The supplier's best response functions are

$$BR_i(e_j) = \begin{cases} r_i^{-1}(r_j(e_j)+\epsilon), & \textit{if } e_i < r_i^{-1}(\bar{e}_j); \\ r_i^{-1}(u), & \textit{otherwise}; \end{cases} \tag{3.2}$$

ii. The only equilibrium exists in the mixed strategies defined by the following cumulative distribution functions:

$$F_n\left(x\right) = \begin{cases} 0, & \textit{if } r_c^{-1}(r_n(x)) < \underline{e}_c; \\ \frac{B_c}{S_n S_c u}\left(c\left(r_c^{-1}(r_n(x))\right) - c\left(\underline{e}_c\right)\right), & \textit{if } \underline{e}_c \leq r_c^{-1}(r_n(x)) < \bar{e}_c; \\ 1, & \textit{if } r_c^{-1}(r_n(x)) \geq \bar{e}_c; \end{cases} \tag{3.3}$$

and

$$F_c\left(x\right) = \begin{cases} 0, & \textit{if } x < \underline{e}_c; \\ 1 - \frac{B_n}{S_n S_c u}\left(c\left(r_n^{-1}(r_c(\bar{e}_c))\right) - c(r_n^{-1}(r_c(x)))\right), & \textit{if } \underline{e}_c \leq x < \bar{e}_c; \\ 1, & \textit{if } x \geq \bar{e}_c; \end{cases} \cdot \tag{3.4}$$

The best-response functions as formulated in Proposition 3.1(i) reflect the desire of both suppliers to become the first-choice supplier, since it generates a strictly higher payoff given the same effort levels. As long as the opponent's effort is sufficiently low, it is always profitable to exert a slightly higher effort. However, if the opponent's effort is high, it is more profitable to reduce the effort level to zero. This structure does not allow for any pure-strategy equilibrium, since one of the suppliers will always prefer to increase her efforts to make the performance ϵ-higher than the rival's performance or drop the effort down to zero.

Therefore, the suppliers have to follow mixed strategies in the equilibrium as described by Proposition 3.1(ii). Each supplier randomizes her effort level on the support $\left[\underline{e}_i, \min\{\bar{e}_i, r_i^{-1}(\bar{e}_j)\}\right]$ with the cumulative distribution function F_n or F_c.

Analysis of equilibrium strategies as formalized in Equations (3.3) and (3.4) allows us to grasp the trade-off between the supplier's equilibrium effort level and the number of teams allocated to her competitor. When discussing the effort levels further in this section, we will refer to the stochastic effort levels following the probability distribution for the mixed strategies as prescribed by Proposition 3.1(ii). Note that lower values of F_n or F_c indicate stochastically higher effort levels. The immediate observation is that for $\beta = 0$, i.e., when the component offered to different teams is fully standardized and thus $B_n = B_c = 1$, the equilibrium effort level is monotonically increasing in the number of teams allocated to the competitor. However, for positive β this relation is not necessarily monotone. This feature is formalized in Proposition 3.2.

Proposition 3.2. *The equilibrium effort level of supplier* n *stochastically increases in* t_c *for* $\beta < \overline{\beta}$ *and decreases otherwise, where*

$$\overline{\beta}(t_c) = \frac{-(1-\alpha)^{t_c}\ln(1-\alpha)}{1-(1-\alpha)^{t_c} + (t_c - 1)(1-\alpha)^{t_c}\ln(1-\alpha)}. \tag{3.5}$$

Furthermore, $\overline{\beta}$ *decreases in* t_c.

The above proposition postulates that for projects with high synergy across teams and low number of teams allocated to the conventional technology supplier, adding an extra team to this supplier will increase the effort exerted by the new technology supplier.

When supplier c receives an extra team in the scenario described above, her probability to develop a component successfully increases significantly, whereas her costs of working with more teams do no change substantially as synergy effect is sufficiently high, i.e., $\beta < \overline{\beta}$. Under these conditions, supplier c tends to increase her effort level to a certain extent. As a result, supplier n faces a decline in probability to become the preferred supplier and under sufficiently low β, she finds it profitable to increase her effort levels as well. Clearly, this logic fails for high β or high t_c because supplier c will experience too high cost of exerting higher efforts to more teams relative to the additional profit, and thus her effort will decrease with the similar effect for supplier n.

Knowing the suppliers' equilibrium strategies, we can construct the manufacturer's objective function as

$$\begin{aligned}\pi(t_n, t_c) &= S_n(r_n(e_n) - u) + S_c(1 - S_n)(r_c(e_c) - u) \\ &\qquad + F_n\Big(r_n^{-1}(r_c(e_c))\Big)S_nS_c\Big(r_c(e_c) - r_n(e_n)\Big) \\ &= S_n(r_n(e_n) - u) + S_c(1 - S_n)(r_c(e_c) - u) + \frac{B_c}{u}\Big(r_c(e_c) - r_n(e_n)\Big)\Big(c\,(e_c) - c\,(\underline{e}_c)\Big)\end{aligned} \tag{3.6}$$

where $e_c \in [\underline{e}_c, \bar{e}_c]$ and $e_n \in [\underline{e}_n, r_n^{-1}(r_c(\bar{e}_c))]$ follow the equilibrium distributions and $c\left(r_i^{-1}(u)\right) \leq \frac{S_i(1-S_j)u}{B_i}$ for $i \neq j$ and $i, j = n, c$.

The immediate observation is $\pi(0, t_c) = \pi(t_n, 0) = 0$ meaning that in the absence of competition the manufacturer's profit is always zero. The reason is that each supplier would exert the minimum sufficient effort to produce component with performance exactly satisfying the target cost, thus leaving the manufacturer without any margin. It is particularly interesting that this result does not depend on values of γ_n and γ_c. Putting it to the extreme, even if the new technology were risk-free, i.e., $\gamma_n = \gamma_c$, the manufacturer would still prefer to allocate at least one team to the conventional technology supplier to benefit from the competition.

3.5 Performance-Contingent Incentive

Now we consider the case when the supplier receives her reward proportionally to the component performance. The supplier's payoff shares some similarities with the target costing incentives. In particular, it depends on whether the supplier's component is the first or the second choice for the manufacturer if both components are successfully developed. Further, for simplicity we will say that a supplier *wins* if her component is the first choice and *loses* otherwise. The supplier's payoff is formalized in Equation (3.7)

$$v_i^P = \begin{cases} S_i \phi r_i(e_i) - c(e_i)B_i, & \text{if } r_i(e_i) > r_j(e_j); \\ S_i(1-S_j)\phi r_i(e_i) - c(e_i)B_i, & \text{if } r_i(e_i) < r_j(e_j); \end{cases} \tag{3.7}$$

where $\phi \in (0,1)$ is the portion of the component performance received by the supplier, $i \neq j$, and $i, j = n, c$. As in the previous section, we start with intuitive analysis of the equilibrium. To simplify further exposition, we denote the supplier payoff if her component performs better as $w_i(e_i)$ and otherwise as $l_i(e_i)$. Consider Figure 3.3 depicting different equilibria depending on the parameters.

The graphs present marginal analysis of the suppliers' decision-making process. If supplier c knew that she would definitely perform worse that her competitor, her marginal performance would be $S_c(1-S_n)\phi r'(e_c)$, and the optimal effort level would be at the intersection of $S_c(1-S_n)\phi r'(e_c)$ and $c'(e_c)$, denoted as $\underline{e}_c^*$. However, if the supplier knew that she would be the first choice of the manufacturer, her

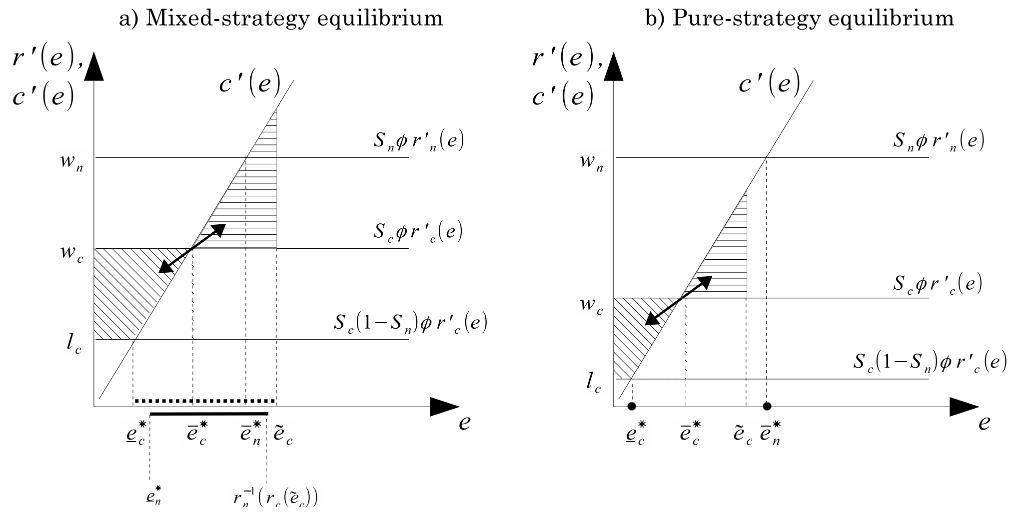


FIGURE 3.3: Supplier's Efforts under Performance-Contingent Contract

marginal performance would increase to $S_c\phi r'(e_c) \geq S_c(1-S_n)\phi r'(e_c)$, and the optimal effort level — to $\bar{e}_c^*$. The area with diagonal hatching represents the gain of supplier c from developing a better performing component than supplier n. As long as this area is non-null, supplier c is eager to exert efforts even higher than $\bar{e}_c^*$ to ensure that her performance is higher. Supplier c finds it optimal to increase the effort until the point when the losses from too high effort, the horizontally hatched area, equalizes with the gains from being the best; this threshold effort level is denoted by $\tilde{e}_c$. Beyond this point (when the horizontal hatching area equalizes the diagonal hatching area), supplier c prefers to develop a worse component at effort level $\underline{e}_c^*$ rather than bearing extra costs of too high efforts.

Figure 3.3(a) depicts the case when $r_n^{-1}(r_c(\tilde{e}_c)) > \bar{e}_n^*$ which means that supplier c finds it optimal to produce a better component than supplier n would produce being the first choice for the manufacturer.

Formally, $\underline{e}_i^* \equiv \arg\max_{e_i}\{l_i(e_i)\} = \arg_{e_i}\left\{\frac{c'(e_i)}{r_i'(e_i)} = \frac{\phi\gamma_i\left(1-(1-\alpha)^{t_i}\right)\left(1-\gamma_j+\gamma_j(1-\alpha)^{t_j}\right)}{1+\beta(t_i-1)}\right\}$ and $\bar{e}_i^* \equiv \arg\max_{e_i}\{w_i(e_i)\} = \arg_{e_i}\left\{\frac{c'(e_i)}{r_i'(e_i)} = \frac{\phi\gamma_i\left(1-(1-\alpha)^{t_i}\right)}{1+\beta(t_i-1)}\right\}$.

Proposition 3.3. *Under the performance-contingent reward,*

i. *The supplier's best response functions are*

$$
BR_i(e_j) = \begin{cases} \underline{e}_i^*, & \text{if } r_j(e_j) > r_i(\overline{e}_i^*) \text{ and } w_i\Big(r_i^{-1}(r_j(e_j)+\epsilon)\Big) < l_i(\underline{e}_i^*); \\ r_i^{-1}(r_j(e_j)+\epsilon), & \text{if } r_j(e_j) > r_i(\overline{e}_i^*) \text{ and } w_i\Big(r_i^{-1}(r_j(e_j)+\epsilon)\Big) \geq l_i(\underline{e}_i^*); \\ \overline{e}_i^*, & \text{if } r_j(e_j) \leq r_i(\overline{e}_i^*). \end{cases} \tag{3.8}
$$

where $\epsilon > 0$, $i \neq j$, *and* $i, j = n, c$.

ii. *If* $\tilde{e}_i < r_i^{-1}(r_j(\overline{e}_j^*))$, *the pure-strategy equilibrium exists which is* $(\underline{e}_i^*, \overline{e}_j^*)$, *where* $\tilde{e}_i \equiv \arg_{e_i}\{w_i(e_i+\epsilon) < l_i(\underline{e}_i^*)\}$, $\forall\, \epsilon > 0$, $i \neq j$, *and* $i, j = n, c$.

iii. *Otherwise, the mixed-strategy equilibrium exists which is defined by the following cumulative distribution functions:*

$$
F_j\Big(r_j^{-1}(r_i(e_i))\Big) = \begin{cases} 0, & \text{if } e_i \leq \underline{e}_i^*; \\ \frac{\phi S_i\big(r_i(\tilde{e_i}) - r_i(e_i)(1-S_j)\big) - \big(c(\tilde{e}_i) - c(e_i)\big)B_i}{\phi r_i(e_i) S_i S_j}, & \text{if } \underline{e}_i^* < e_i \leq \tilde{e}_i; \\ 1, & \text{if } e_i > \tilde{e}_i. \end{cases} \tag{3.9}
$$

where $i \neq j$ *and* $i, j = n, c$.

In words, Proposition 3.3(i) shows that the best response depends on how much effort the other supplier exerts. If she exerts high efforts, supplier i is better off by exerting the optimal effort for the *losing case*, $\underline{e}_i^*$. On the other extreme, when e_j is sufficiently low, supplier i will exert the optimal effort for the *winning case*, $\overline{e}_i^*$. However, for some intermediate efforts, supplier i will exert such an effort level that allows her to have a higher performance than supplier j, although it does not maximize $w_i(e_i)$ or $l_i(e_i)$ individually. Interestingly, this intermediate effort level of the supplier j leads to higher effort level of the supplier i. Formally, $r_i^{-1}(r_j(e_j)+\epsilon) > \overline{e}_i^* > \underline{e}_i^*$.

Given this structure, a pure-strategy equilibrium may exist under certain parameters as formalized in Proposition 3.3(ii). There exist two possible pure-strategy equilibria, which are $(\overline{e}_i^*, \underline{e}_j^*)$ for $i \neq j$, $i, j = n, c$. The necessary condition for this equilibrium structure to hold is $w_i\Big(r_i^{-1}(r_j(\overline{e}_j^*)+\epsilon)\Big) < l_i(\underline{e}_i^*)$, which means that supplier i is better off by maximizing the losing case objective function rather than trying to outperform supplier j. Note that the above condition holds if $r_j(\overline{e}_j^*) > r_i(\overline{e}_i^*)$, since $w_i(\overline{e}_i^*) > l_i(\underline{e}_i^*)$ and supplier i would always adopt $\overline{e}_i^*$ effort level otherwise. It is curious to see how $\overline{e}_i^*$ depends on the parameters: it is increasing in γ_i and α_i, while it is not monotone in t_i — it is increasing for sufficiently low t_i and then decreasing for higher t_i.

Finally, Proposition 3.3(iii) reveals the nature of the mixed-strategy equilibrium which shares some structural similarities with the equilibrium under the target costing incentive scheme. Both players randomize their effort levels on the interval between 0 and some maximum threshold level. For the performance-contingent incentive, this level $\tilde{e}_i$ is determined as such a level that supplier i prefers to develop the second-best component with effort $\underline{e}_i^*$ rather than exert any efforts beyond it.

3.6 Effect of Supplier Competition on Manufacturer Profit

In this section, we attempt to make a step further in our analysis and estimate the competition effect on the manufacturer's profit rather than on the other supplier's efforts. This raises the complexity of the problem, and to ensure analytical tractability, we allow suppliers to exert only either low or high efforts, denoted as e_L and e_H. Table 3.1 presents the expected payoffs of the suppliers under this effort structure.

S_n \ S_c	Low effort	High effort
Low effort	$S_n y_n(e_L) - c(e_L)B_n$ $(1-S_n)S_c y_c(e_L) - c(e_L)B_c$	$S_n(1-S_c)y_n(e_L) - c(e_L)B_n$ $S_c y_c(e_H) - c(e_H)B_c$
High effort	$S_n y_n(e_H) - c(e_H)B_n$ $(1-S_n)S_c y_c(e_L) - c(e_L)B_c$	$S_n y_n(e_H) - c(e_H)B_n$ $(1-S_n)S_c y_c(e_H) - c(e_H)B_c$

TABLE 3.1: Supplier Payoff Matrix

In the payoff matrix, $y_i(\cdot) = u$ for target costing contract and $y_i(\cdot) = \phi r_i(\cdot)$ for performance-contingent contract, $i = n, c$. Let $\rho \equiv \frac{S_n y_n(e_H) - S_n(1-S_c)y_n(e_L) - \Delta_c B_n}{S_n S_c y_n(e_L)}$ and $\mu \equiv \frac{\Delta_c B_c - S_c(1-S_n)(y_c(e_H) - y_c(e_L))}{S_n S_c y_c(e_L)}$, where $\Delta_c = c(e_H) - c(e_L)$. When considered for particular team allocation of t_n and t_c, we will denote these probabilities as $\mu_{t_n t_c}$ and $\rho_{t_n t_c}$.

Proposition 3.4. *The equilibrium supplier efforts for supplier N and C under both target costing and performance-contingent contracts are as follows:*

- (e_L, e_L) *if* $\mu \geq 1$*, the low effort equilibrium;*
- (e_L, e_H) *if* $\mu < 1$ *and* $\rho \leq 0$*, the low risk equilibrium;*
- *supplier n (c) exerts e_L with probability μ (ρ) and e_H with probability $1-\mu$ ($1-\rho$) if $\mu < 1$ and $\rho > 0$, the mixed-strategy equilibrium.*

Proposition 3.4 describes equilibria in general form for both target costing and performance-contingent contracts. However, note that despite the apparent similarity, the separating conditions are different for the two contracts. For target costing contract, the parameters μ and ρ will take form of $\mu^T = \frac{(c(e_H) - c(e_L))B_c}{S_n S_c x_c(e_L)}$ and $\rho^T = 1 - \frac{(c(e_H) - c(e_L))B_n}{S_n S_c x_n(e_L)}$, respectively. We define three equilibrium types: low effort equilibrium occurring when both suppliers prefer to exert minimal efforts, low risk equilibrium — when conventional technology supplier chooses to exert high efforts, and mixed-strategy equilibrium — when different effort choices are admissible.

In the previous section, we could see that synergy level have crucial effect on the suppliers' equilibrium behavior defining their reaction to additional competition. First, we examine how the manufacturer's profit changes in synergy level. Common sense would suggest that higher synergy should always benefit the manufacturer as it allows the suppliers to exert efforts for multiple teams at lower costs. Equation (3.10) represents the first-order derivative of the manufacturer's profit with respect to β.

$$\frac{\partial \pi^T}{\partial \beta} = \frac{uS_n(t_c-1)(r_n^H-r_n^L)-uS_c(1-S_n)(t_n-1)(r_c^H-r_c^L)-\Delta_c(t_n+t_c-2)(r_c^H-r_n^L)}{2(t_n-1)(t_c-1)(r_c^H-r_n^L)\Delta_c}, \tag{3.10}$$

where $\Delta_c = c(H) - c(L)$.

From (3.10), we conclude that $\frac{\partial \pi^T}{\partial \beta} > 0$, if t_c is sufficiently high relative to t_n. It means that synergy hurts the manufacturer's profit (recall that higher β means lower synergy) when supplier c gets high number of teams, while synergy leads to increase in the manufacturer's profit otherwise. Intuitively, when cross-team synergy is low, supplier c knows that supplier n is less likely to exert high effort and override her, and that is why supplier c is ready to bear additional costs in pursuit of superior performance. More formally, ρ^T decreases whereas μ^T increases in β. Therefore, when supplier c has sufficient number of teams, the manufacturer's profit will be higher under low synergy levels, with the opposite holding otherwise.

Now suppose that $m = 3$ under the target costing scheme, i.e., the manufacturer needs to allocate three teams. For concreteness, let us introduce a performance function for supplier n as $r_n(e) = e$ and for supplier c as $r_c(e) = \frac{e}{k}$, $k \geq 1$. To characterize the optimal team allocation, we introduce two measures of the project success probability. Let $V \equiv k\gamma_n + \gamma_c$ and $W \equiv k\gamma_n + \gamma_c\Big(1 - \gamma_n\alpha(2-\alpha)\Big)$. In this notation, V represents a weighted measure of success of either new or conventional technology where new technology is taken with a higher weight due to higher performance. Then W represents another measure of success with a lower weight for the conventional technology reflecting the idea that it will be needed only if the new technology fails which happens with probability $\big(1-\gamma_n\alpha(2-\alpha)\big)$ when $t_n = 2$.

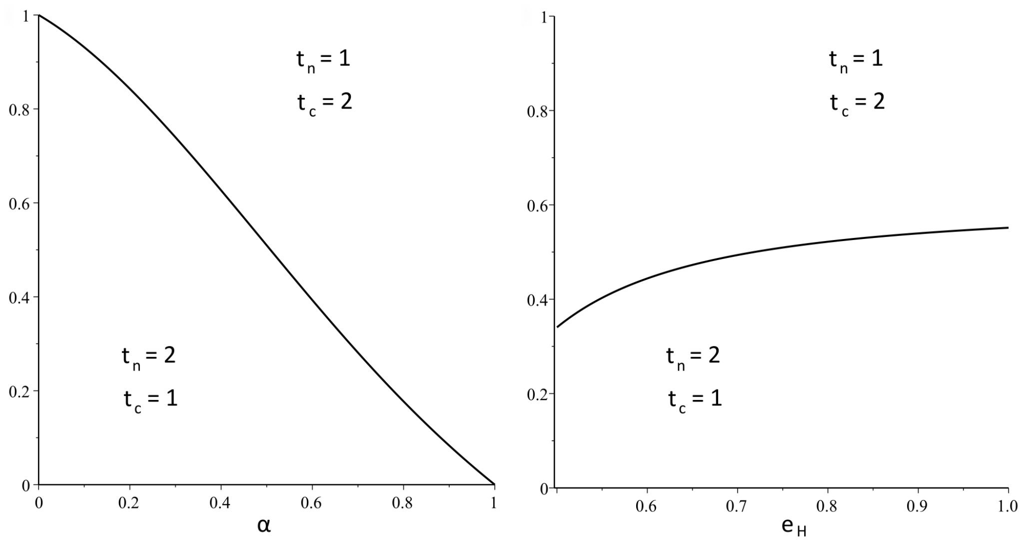
Proposition 3.5. *For $m = 3$, if the manufacturer chooses to induce competition, the optimal team allocation is $t_n = 2$, $t_c = 1$ if $\beta > \bar{\beta}_3$ and $t_n = 1$, $t_c = 2$ if $\beta \leq \bar{\beta}_3$, where*

$$\bar{\beta}_3 = \frac{V}{W} - \frac{k\gamma_n e_H - \gamma_c e_L}{W\mu_{21}^T(e_H - e_L)}. \tag{3.11}$$

Proposition 3.5 explains that it is optimal to allocate more teams to the new technology supplier when the synergy level is sufficiently low, and otherwise the manufacturer needs to allocate more teams to the conventional technology supplier. The exact mechanism for this choice in more general form is discussed in Section 3.4 and relates to different suppliers' response to competition depending on the synergy level.

As W and μ_{21}^T are increasing in α, we can easily see that $\bar{\beta}_3$ is non-increasing in α. It means that at lower values of team-specific risk the manufacturer is better off by allocating the second team to the new technology supplier at lower values of β. At the same time, $\bar{\beta}_3$ is non-decreasing in e_H (similarly, non-increasing in e_L) as long as $e_H > e_L$. Figure 3.4 presents these relationships graphically where the line is the value of $\bar{\beta}_3$.

The main driver for manufacturer's allocation of more teams to supplier c under low team-specific risk, α, is that the supplier n is more likely to exert low efforts at higher α while supplier c exhibits the opposite equilibrium behavior. The intuition is that supplier n, being the first choice for the manufacturer but facing high uncertainty, prefers to reduce the cost of efforts and to rely on the chance that supplier c decides to exert low effort too or all t_c fail. At the same time, supplier



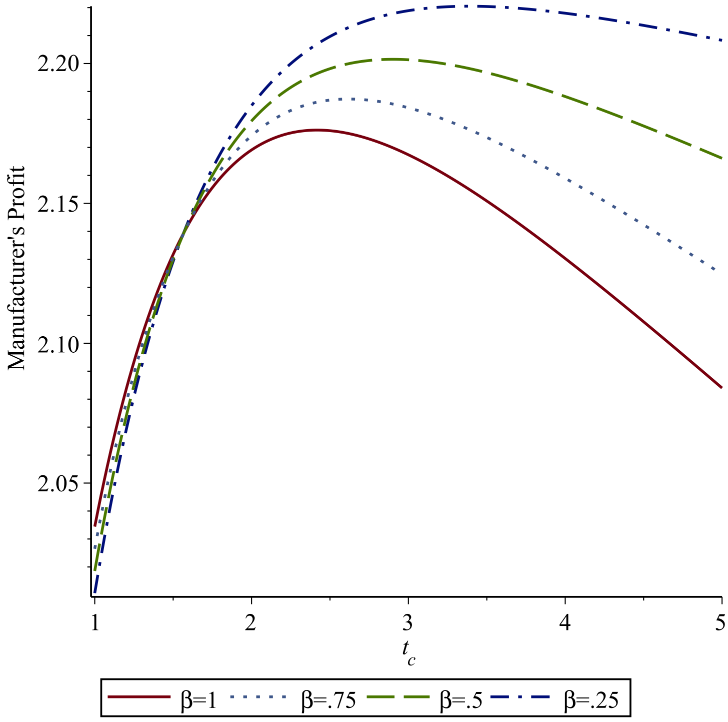
$e_H = .75$ $\alpha = .5$

$e_L = 0.25, \gamma_n = .5, \gamma_c = 0.75, u = .4$

FIGURE 3.4: Optimal Team Allocation for $m = 3$

c tries to exploit her chance to win the race by exerting higher efforts (and hence getting higher component performance in case of success) than supplier n and becoming the first choice for the manufacturer. The opposite relation holds for e_H representing the difference between the admissible effort levels. Higher effort difference means that a supplier needs to bear high cost to switch from low to high effort state. This is relatively more important for conventional technology supplier as she might fail to receive the mass production contract even if exerting high efforts and succeeding in the development. Hence, the manufacturer should optimally choose to allocate more teams to supplier n as the cost of effort difference increases.

The next step is to identify the effect of competition on the manufacturer's profit which might potentially depend on the synergy level. Figure 3.5 shows the effect of higher number of teams allocated to supplier c on the manufacturer's expected profit. As we expected, as long as the number of teams is sufficiently small, each additional team leads to the increase in the manufacturer's profit. This is due to the enhanced competition and higher effort levels induced from supplier n. However, when supplier c receives a sufficient number of teams, further increase leads to a decline in the manufacturer's profit due to lowering efforts of the competing supplier.



$$r_n^H = 5, r_c^H = 4.5, r_n^L = 4, r_c^L = 3.5, \alpha = 0.75, e_L = 0.5, e_H = 0.55, \gamma_n = \gamma_c = 0.5,$$
$$t_n = 2, u = 1$$

FIGURE 3.5: Competition Effect on Manufacturer's Profit

Furthermore, we can see that with lower β, i.e., higher synergy of efforts across teams, the manufacturer's profit starts decreasing in t_c at a larger value of t_c. Proposition 3.2 lays intuition for this effect: High synergy level ensures that the equilibrium effort level for supplier n will stochastically increase until a higher value of t_c, which translates directly to the manufacturer's profit.

3.7 Conclusion

We have modeled the product development scenario when the manufacturer of the new product deploys multiple parallel teams to complete the product development. Each team can be allocated to a supplier of the key component to be developed. After the development stage, the manufacturer chooses the design developed by one of the teams and grants a contract for component procurement at the mass production stage to the supplier working with this team.

The main insight of our analysis is that tougher competition between suppliers, arising from additional teams allocated to one of them, may lead to higher equilibrium efforts exerted by another supplier. It complements the classical insight proposed by Fullerton and McAfee (1999) suggesting that two participants of a contest are sufficient to induce the competition and further competition arising from involvement of more participants will inevitably drive the equilibrium efforts down. The intuition behind this effect is that more participants imply lower probability of success for each and thus make the expected gain less while the costs are unaffected, which results in lower efforts. We, however, show that if competition intensifies not through involvement of more participants (suppliers in our setting) but rather through improvement of their characteristics (allocation of more teams in our setting), the equilibrium efforts for the participants with unaffected characteristics can increase.

We have found this effect under two wide-spread contracting schemes for the product development stage: fixed-payment (target costing) contract and performance-contingent contract. Under both contract types, we have discovered that an important factor determining the effect of competition on the effort levels is the synergy level which suppliers experience working with multiple teams. If significant portion of suppliers' efforts can be easily distributed across multiple teams without additional costs, we say that the product development project implies high synergy level. However, if each team requires individualistic approach and most efforts need to be doubled to be applied to the second team, the project implies low synergy levels. Using this terminology, we have shown that the necessary condition for competition to boost equilibrium efforts is high synergy levels. From managerial perspective, it means that the manufacturer of the new product needs to deploy larger number of teams when the project implies high synergies, and, more importantly, allocate them equally to the suppliers even if one supplier is significantly better than another.

Another important observation is that the competition starts to decrease the equilibrium efforts of a supplier if another supplier receives sufficiently high number of teams which makes her chances to succeed much greater than ones of her rival. In such a case, for the manufacturer it might be more beneficial to reduce the number of teams allocated to that supplier as high number of teams may hurt the manufacturer's profit even though the team maintenance is assumed costless in our model.

Finally, we confirm that higher competition can lead not only to higher efforts of suppliers but also to higher manufacturer's profit. Further research is needed to investigate the manufacturer's optimal choice between the two contract types. While in this chapter, we considered the allocation of teams as a decision variable, one can reasonably consider the contract terms (target cost u and portion of revenue ϕ) as decision variables, and compare the contracts under the optimal terms and the optimal team allocation.

Chapter 4

Supplier Incentives for Component Testing

4.1 Introduction

Consistently with the previous chapters, we consider a manufacturer developing a new product and involving a supplier to develop a component of the future product. Having lack of knowledge about the underlying technology for this component, the manufacturer has to rely on the supplier's opinion whether the component performs sufficiently well and is worth to be placed in the new product. There is some evidence suggesting that suppliers can sometimes release their component to the manufacturer without proper checks of its performance. In this chapter, we investigate the suppliers' incentives and discuss the ways to make them more responsible for the final product success.

Consider the following example. In 2003 Boeing launched the development project of a new aircraft, Dreamliner, one of which key features was supposed to be a considerably smaller weight in comparison to existing aircraft models. Pursuing this goal, Boeing decided to replace the traditional for the aviation industry heavy nickel-cadmium battery with the novel substantially lighter lithium-ion battery (Adolph, 2013). In 2005 Boeing approved Yuasa, a Japanese subcontractor, for the development and subsequent supply of lithium-ion batteries. The supplier developed the required battery to specifications provided by Boeing, and by 2013 mass production of the lithium-ion batteries had started.

However, shortly after Boeing sold its first new jets, several of the new aircraft caught fire, and Boeing had to land the entire Dreamliner fleet for several months to identify and fix the cause of the problem. Although the grounding-related expenses were largely covered by insurance (Tsikoudakis, 2013), Boeing suffered from around six billion dollars in cash drag during 2013 (Lowy, 2013), as well as lost sales and reputation loss. Following the incidents, it was identified that the cause of inflammations was battery overheating because the supplier had not performed additional tests to verify that their batteries would work stable with aircraft systems. The supplier's quality control was decent for the requirements of automotive industry but proved to be not conservative enough for aviation (Wald and Mouawad, 2013). The Yuasa's President commented after the investigation referring to lessons for the future: "Instead of merely following instructions and making batteries, we should also study their instructions, collect data ourselves and make suggestions" (Kubota and Osada, 2013). Although the supplier suffered from some reputation loss affecting her non-aviation business (Motavalli, 2013), no real penalties could be applied for the battery failures (Cooper and Mukai, 2013).

The root problem is that the supplier may have little incentives to perform the tests following the component development, while the manufacturer may not have enough expertise to perform and even identify the necessary tests on his own. In this chapter, we investigate the incentives the existing contracts create for suppliers and the ways how manufacturers can modify them to induce a better component testing from suppliers.

4.2 Literature Review

From the agency theory perspective, our problem is related to the class of principal-agent models with endogenous information (Laffont and Martimort, 2002, p. 395). Crémer and Khalil (1992) investigate a setting similar to ours with the exception that they do not allow the agent (the supplier) to fail and, consequently, the principal (the manufacturer) cannot suffer from the agent's failure. They find that the optimal contract does not incentivize the agent to gather information (perform tests), the result which is very far from our findings. Crémer et al. (1998) allow the agent to gather information prior to the contract offer by the principal, which makes the agent decision strategic. Szalay (2009) further develops this problem but allows the information to be continuous in the amount of effort exerted for its gathering. In our model, however, the agent starts the information gathering after receiving the contract terms, and otherwise she would never start the component development in the first place. Lewis and Sappington (1993) consider the problem when the agent's efforts may or may not lead to private information, which is unobservable by the principle, and thus they do not focus on the issue of the agent's decision to gather information.

The essence of the problem lies within the realm of the literature on product recalls and division of liability between the parties involved, although our problem of product failure is more general and not limited to the recall cases only. Another prominent difference is that product recall literature mostly looks for the ways to incentivize the supplier to improve the component quality, while we concentrate on the preceding stage — when the supplier may decide to learn the component quality and the improvement decision may be never on the agenda.

Jarrell and Peltzman (1985) were one of the first to analyze the total cost of product recalls in various industries. Their main conclusions state that the major loss from a product recall is often immaterial taking the form of goodwill loss, and moreover a product recall produces significant negative externalities implying losses for other stakeholders who are not responsible for the recall. Altough debatable (Hoffer et al., 1988), this idea of goodwill loss spread to the shareholders is wide-spread in the literature (e.g., Rupp, 2004), which is especially strong for the suppliers. In line with that research, we allow for supplier's and manufacturer's separate goodwill costs, even though the supplier is responsible for the product failure. Chao et al. (2009) present a deep analysis of the supplier incentives to improve the product quality under different contracts defining the recall cost sharing proportion between manufacturer and supplier depending on who is responsible for the product quality problem. Our focus is, however, on the cases when the supplier's fault is not a subject for dispute, as in the battery failure example. Baiman et al. (2000) construct the optimal contracts in a setting when the manufacturer can perform appraisal tests to evaluate the component quality, while we consider a scenario when such tests are infeasible due to lack of expertise on the manufacturer's side. Furthermore, the Baiman et al. (2000) discussion largely builds around the quality improvement decision of the supplier rather than decision to learn the quality.

4.3 Model

We intend to model the supplier's decision on performing additional tests for the key component she develops. After developing the component, the supplier needs to decide whether or not to perform tests of the new component at cost $c > 0$. If the supplier chooses to perform the tests, she learns the probability of the component success θ which is a draw from a probability distribution with the cumulative density function $F(\theta)$ and the support $[0, 1]$. If the tests are not performed, the supplier knowledge remains limited to the distribution $F(\theta)$. This

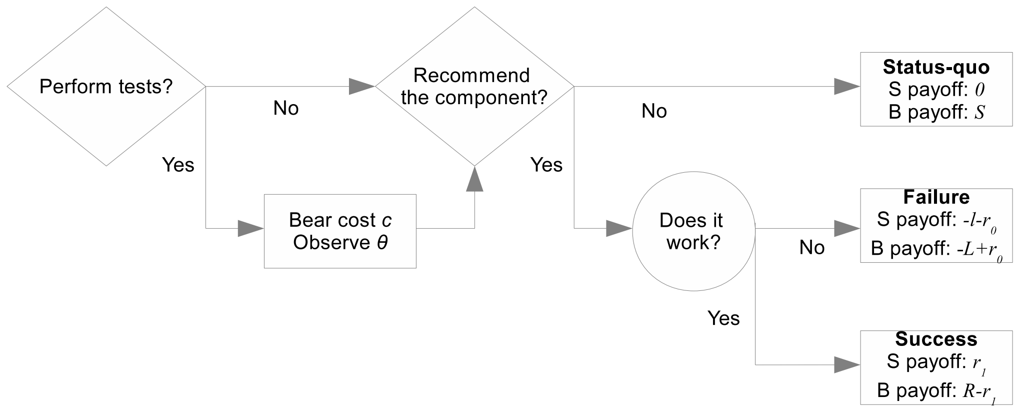


Figure 4.1: Decision Tree

modeling approach allows to capture the difference in the degree of uncertainty which the supplier experiences before and after performing the tests. At the next stage, the supplier decides whether or not to recommend the new component for the final product, i.e., to release the component to the manufacturer or claim that the component might be inferior and quit the collaboration. The game tree (after the manufacturer offered and the supplier accepted the contract) is depicted in Figure 4.1. The rhombuses represent the supplier's decisions and the circle stands for the nature's decision (stochastic event).

If the component proves to be successful, its one-dimensional contribution to the final product is denoted as R. The same measure for the off-shelf component, the manufacturer's outside option, is $S < R$. If the component is accepted for the mass production but it fails subsequently, the manufacturer bears total losses of L. If the supplier chooses not to recommend the component for the new product and quits the collaboration, her payoff is normalized to 0. However, if she does recommend the component, her payoff depends on the component success. If the component works well, the supplier is rewarded with $r_1 \leq R - S$. However, in case of failure, the supplier bears the reputation loss l and incurs a penalty from the manufacturer r_0. Our analysis will also cover the case of the limited supplier liability where we set $r_0 = 0$. Hence, r_0 and r_1 are the manufacturer's outcome-dependent decision variables.

We denote the supplier action as $q_i = \{0, 1\}$ where 0 means that the supplier does not recommend the new component, 1 means that she recommends the new component, and $i = 0, 1$ indicates the supplier information (0 if the supplier has not performed the tests and thus is ignorant about θ and 1 if she has performed the tests and knows θ precisely).

4.4 Optimal Supplier Behavior

We start with the analysis of the optimal supplier's decision to release the component or to quit the development. At this stage, the supplier has already either acquired additional information on the component quality through testing or not. Proposition 4.1 formalizes the intuition for this decision.

Proposition 4.1. *The optimal action for the*

- *informed supplier is*

$$q_1^* = \begin{cases} 1 & \textit{if } \theta \geq z \\ 0 & \textit{if } \theta < z \end{cases}, \tag{4.1}$$

  where $z = \frac{l+r_0}{r_1+l+r_0}$*, and for the*

- *uninformed supplier is*

$$q_0^* = \begin{cases} 1 & \textit{if } \mathrm{E}_\theta\{\theta r_1 - (1-\theta)(l+r_0)\} \geq 0 \\ 0 & \textit{if } \mathrm{E}_\theta\{\theta r_1 - (1-\theta)(l+r_0)\} < 0 \end{cases}. \tag{4.2}$$

The important piece of intuition is that for the informed supplier there exists a certain well-defined threshold for θ which allows the supplier to decide on whether to release the component or not to proceed with the development project, and the supplier releases the component only if the observed θ is above the threshold. This threshold is increasing in the supplier's losses, both reputational and monetary, in case of failure and decreases in the supplier's gains in case of success.

The next step is to understand how the supplier makes her decision on whether to move to the informed state through performing the tests or remain ignorant about the component success probability. As this decision depends on a particular contract offered by the manufacturer, we consider it separately for different admissible contracts further in this section. After investigating the first-best scenario when the supplier and manufacturer are integrated, we focus on reward contract which does not allow for any penalties for supplier in case of component failure and residual claimant contract which allows for the penalties. Finally, we will construct the efficient contract which is able to achieve the first-best outcome but, as we will see, is hardly possible for practical implementation.

4.4.1 First-Best Analysis

Here we analyze the outcome arising if manufacturer and supplier are a single centralized decision maker, i.e., the first-best outcome which will serve as a benchmark for further analysis. Our objective is to find the optimal level of testing which would be achieved in a situation when the incentives of the supplier and the manufacturer coincide. To find this optimal level of testing, we solve the problem backwards, starting with the supplier's decision on release/quitting. Following the framework set by Proposition 4.1, we find that the optimal action for the informed supplier is

$$q_1^* = \begin{cases} 1 & \text{if } \theta(R-S) - (1-\theta)L \geq 0 \\ 0 & \text{if } \theta(R-S) - (1-\theta)L < 0 \end{cases} = \begin{cases} 1 & \text{if } \theta \geq z \\ 0 & \text{if } \theta < z \end{cases}, \tag{4.3}$$

where $z = \frac{L}{R-S+L}$ with the corresponding optimal expected payoff of $\pi_1^* = \Big(1 - F(z)\Big)\mathrm{E}_{\theta\geq z}\{\theta(R-S)-(1-\theta)L\} - c$.

If the tests have not been performed, the optimal action is

$$q_0^* = \begin{cases} 1 & \text{if } \mathrm{E}_\theta\{\theta(R-S)-(1-\theta)L\} \geq 0 \\ 0 & \text{if } \mathrm{E}_\theta\{\theta(R-S)-(1-\theta)L\} < 0 \end{cases}, \tag{4.4}$$

and the optimal expected payoff is $\pi_0^* = \Big(\mathrm{E}_\theta\{\theta(R-S)-(1-\theta)L\}\Big)^+$.

Clearly, the integrated decision-maker performs the tests only if $\pi_1^* \geq \pi_0^*$, in particular,

$$\Big(1 - F(z)\Big)\mathrm{E}_{\theta\geq z}\{\theta(R-S)-(1-\theta)L\} - c \geq \Big(\mathrm{E}_\theta\{\theta(R-S)-(1-\theta)L\}\Big)^+, \tag{4.5}$$

where $z = \frac{L}{R-S+L}$. Then, the decision to test or not to test the component depends on the testing cost as described in Proposition 4.2.

Proposition 4.2. *If* $\mathrm{E}_\theta\{\theta(R-S)-(1-\theta)L\} \geq 0$, *testing is optimal if*

$$c \leq \int_0^z \Big((1-\theta)L - \theta(R-S)\Big) f(\theta)\mathrm{d}\theta = \overline{c}_1, \tag{4.6}$$

and otherwise — if

$$c \leq \int_z^1 \Big(\theta(R-S) - (1-\theta)L\Big) f(\theta)\mathrm{d}\theta = \overline{c}_0. \tag{4.7}$$

Proposition 4.2 denotes the highest testing costs when the supplier chooses to perform tests as $\overline{c}_1$ when the expected benefit from trying a new component without testing is positive and $\overline{c}_0$ otherwise. These cost levels will serve as benchmarks for the further analysis. The first scenario is very likely when the potential goodwill loss is sufficiently small or the potential benefits of the new component far outweigh the losses of possible failure.

4.4.2 Reward Contract

We start with the special case when the supplier cannot be obliged to pay any penalty in case of component failure, i.e., $r_0 = 0$, and the only loss she bears is the reputation loss l. The purpose is to investigate the parties' incentives under a contract often taking place in practice. Another interpretation for this contract type can be that the supplier has limited liability, and hence no significant penalty can be charged as the supplier might declare bankruptcy. The supplier will perform the tests as long as her expected payoff after testing is not less than her expected payoff without testing:

$$\Big(1 - F(\hat{z})\Big)\mathrm{E}_{\theta \geq \hat{z}}\{\theta r_1 - (1-\theta)l\} - c \geq \Big(\mathrm{E}_{\theta}\{\theta r_1 - (1-\theta)l\}\Big)^+, \tag{4.8}$$

where $\hat{z} = \frac{l}{r_1 + l}$ as obtained from Proposition 4.2 when $r_0 = 0$. The immediate observation is that $\lim_{l \to 0} \hat{z} = 0$, in which case (4.8) never holds. This property is independent of the value of r_1 as long as $r_1 \neq 0$. It means that when the supplier's reputation loss in case of failure is low (close to 0), the strategy of testing the component is never optimal for her. This result is fairly intuitive: If there is no penalty in case of failure, then the supplier will always try the new component, which means that there is no rationale for the supplier to test the component before installation. Therefore, the only incentive to perform the component tests arises from the reputation loss in case of failure.

First, we need to check if there exists such r_1 which would lead to the efficient outcome described in Section 4.4.1. As θ cannot be specified in a contract, the only feasible form is $r_1 = R - S - T$, where $R - S$ is the additional value created in case of the component success and $T \leq R - S$ is the manufacturer's portion of it. Then, we can rewrite (4.8) as

$$c \leq \int_0^{\hat{z}} \Big((1-\theta)l - \theta(R-S) + \theta T\Big) f(\theta)\mathrm{d}\theta, \tag{4.9}$$

if $\mathrm{E}_\theta\{\theta(R-S-T) - (1-\theta)l\} \geq 0$, where $\hat{z} = \frac{l}{R-S+l-T}$. Note that the right-hand side of (4.9) is non-decreasing in T, which is non-trivial. It means that the less the supplier expects to receive in case of the component success, the more she is prone to test the component. Intuitively, one can think about it in the following way. When the expected payoff in case of success is high, the supplier is very likely to install the component anyway, with or without testing, i.e., to some extent, regardless of the testing results, that is why the testing is less attractive in this case. In other words, the value of testing for the supplier is smaller when the reward for the successful component is high. However, when the expected gain in case of success is lower, the supplier's decision will depend on the test results, thus increasing the value of testing and incentivizing the supplier to perform the tests.

Note that if $\mathrm{E}_\theta\{\theta(R-S-T) - (1-\theta)l\} < 0$, then $c \leq \int_{\hat{z}}^1 \Big(\theta(R-S) - (1-\theta)l - \theta T\Big) f(\theta)\mathrm{d}\theta$, making the right-hand side non-increasing in T. Therefore, the optimal T is not necessarily the highest possible T satisfying the supplier participation constraint. In other words, the supplier's expected payoff in case of blind recommendation decreases in T faster than the supplier's expected payoff in case of testing. Proposition 4.3 describes the optimal T^*.

Proposition 4.3. *(i) If* (4.9) *holds at* $T = \underline{T}$*, then*

$$T^* = \arg\max_{T\in[\underline{T},\overline{T}]} \left\{\int_{\hat{z}}^1 \Big(\theta T - (1-\theta)L\Big) f(\theta)\mathrm{d}\theta\right\}, \tag{4.10}$$

where $\underline{T} = R - S - l\left(\frac{1}{\mathrm{E}_\theta\theta} - 1\right)$
and $\overline{T} = \arg_T\left\{\int_{\hat{z}}^1 \Big(\theta(R-S) - (1-\theta)l - \theta T\Big) f(\theta)\mathrm{d}\theta = c\right\}$.

(ii) Otherwise, $T^* = \underline{T}$.

A noteworthy observation is that the lower bound for the optimal manufacturer's portion, $\underline{T}$, is decreasing in the supplier's reputation loss l. It means that the higher the supplier's reputation loss, the higher portion of the pie the manufacturer may need to promise to the supplier in case of success. It means that the manufacturer may need to compensate the supplier for her high potential reputation losses. However, the exact value of T^* will largely depend on the distribution of θ.

4.4.3 Residual Claimant Contract

The literature suggests that under endogenous information agency problems the contracts making the supplier residual claimant for the total profit can achieve the first-best outcome. The intuition is straightforward: If the supplier needs to maximize the same objective function as the manufacturer but then gives away some fixed amount, her optimal decisions will be identical to the manufacturer's. We would like to verify if this holds for our specific problem.

To align the supplier's objective function with the manufacturer's, the reward and penalty should be $r_1 = R-S-T$ and $r_0 = L-l+T$, respectively, where $T < R-S$ is the payment to the manufacturer which is made independent of the outcome. For residual claimant contract, we assume a risk-neutral supplier which was not a necessary assumption for the reward contract. This payment structure ensures that the supplier obtains a residual from the total profit or loss, $R - S - T$ or $-L - T$, respectively. The condition for the supplier to perform tests becomes

$$\Big(1-F(\tilde{z})\Big)\mathrm{E}_{\theta\geq\tilde{z}}\{\theta(R-S)-(1-\theta)L-T\}-c \geq \Big(\mathrm{E}_{\theta}\{\theta(R-S)-(1-\theta)L-T\}\Big)^{+}, \tag{4.11}$$

where $\tilde{z} = \frac{L+T}{R-S+L}$. We can see that contrary to our intuition the testing region under (4.11) does not generally coincide with that region under (4.5). To see it more clearly, we will rewrite the (4.11) when $\mathrm{E}_\theta\{\theta(R-S)-(1-\theta)L\} \geq 0$ as

$$c \leq \bar{c}_1 + F(z)T + \int_z^{\tilde{z}} \Big(T + (1-\theta)L - \theta(R-S)\Big) f(\theta)\mathrm{d}\theta, \qquad (4.12)$$

From (4.12) we can see that the supplier is even more eager to test the design rather than the single decision-maker. However, excessive testing, contrary to the common sense, does not constitute an efficient (or superior to efficient) outcome. The supplier indeed performs testing even if the testing costs are prohibitively high. At the same time, the supplier is much less likely to release the component to the manufacturer due to high penalties consisting of both reputation and monetary components.

The underlying reason for not achieving the efficient outcome is that in our model the supplier has an outside option, i.e., she can quit the collaboration and thus avoid paying T to the manufacturer. This option creates sufficient distortion to the model to prevent the residual claimant contract from achieving the efficient (first-best) outcome. The interesting observation is that as T increases, the supplier is ready to perform tests at higher costs. The latter occurs due to a higher value of the option to quit for the supplier, as the loss in case of component failure increases, and thus she prefers to gather additional information even at higher costs.

To find the optimal T, we need to formally define the manufacturer's payoff and objective function. The manufacturer obtains S if the component is not installed, $T-l$ is the component is installed but fails, and T if the component is successfully installed. From (4.12) we can see that if (4.11) holds for some value of T, then it will hold for all $T' \geq T$. Note also that for $T=0$, (4.11) is equivalent to (4.5).

The manufacturer's expected payoff if the supplier chooses to perform the tests is

$$\pi_1 = (1-F(\tilde{z}))\mathrm{E}_{\theta\geq\tilde{z}}\Big(\theta T+(1-\theta)(T-l)\Big)+F(\tilde{z})S = (1-F(\tilde{z}))\Big(T-\mathrm{E}_{\theta\geq\tilde{z}}(1-\theta)l\Big)+F(\tilde{z})S, \tag{4.13}$$

and if the supplier does not hold the tests, the manufacturer's expected payoff is

$$\pi_0 = \mathrm{E}_\theta\Big(\theta T + (1-\theta)(T-l)\Big) = T - \mathrm{E}_\theta(1-\theta)l. \tag{4.14}$$

Therefore, the optimal T can be found as Proposition 4.4 prescribes.

Proposition 4.4. *(i) If* (4.5) *holds, then the optimal* $T^* = \widetilde{T}$, *where*

$$\widetilde{T} = \arg_T\left\{\Big(1-F(\tilde{z})\Big)\mathrm{E}_{\theta\geq\tilde{z}}\{\theta(R-S)-(1-\theta)L-T\}-c=0\right\}. \tag{4.15}$$

(ii) If (4.5) *does not hold, and*

- $\pi_1(\widetilde{T}) \geq \pi_0(\widetilde{T})$ *and* (4.11) *holds at* $T = \widetilde{T}$, *then* $T^* = \widetilde{T}$*;*
- (4.11) *does not hold at* $T = \widetilde{T}$, *then* $T^* = \mathrm{E}_\theta\{\theta(R-S)-(1-\theta)L\}$*;*
- (4.11) *holds at* $T = \widetilde{T}$ *and* $\pi_1(\widetilde{T}) < \pi_0(\widetilde{T})$, *then* $T^* = \underset{\sim}{T}$, *where*

$$\begin{aligned}\underset{\sim}{T} = \arg_T\Big\{\Big(1-F(\tilde{z})\Big)&\mathrm{E}_{\theta\geq\tilde{z}}\{\theta(R-S)-(1-\theta)L-T\}-c\\ &= \Big(\mathrm{E}_\theta\{\theta(R-S)-(1-\theta)L-T\}\Big)^+\Big\}.\end{aligned} \tag{4.16}$$

Proposition 4.4(i) says that if (4.5) holds, then the manufacturer will set the highest possible T ensuring the supplier's participation, which is $\widetilde{T}$. This result is based on the important insight that if the supplier chooses to test under some low level of the manufacturer's portion of profit, the supplier will always choose to test under some higher level of the manufacturer's portion, unless she chooses to quit the development process ($\forall\ T > \widetilde{T}$).

Proposition 4.4(ii) deals with several possible parameter configurations. If the supplier chooses to test at $T = \widetilde{T}$ and it is the preferred manufacturer's option, the latter sets $T^* = \widetilde{T}$. However, if the supplier does not choose to test even at $T = \widetilde{T}$, it means that it is impossible to incentivize the supplier to test regardless of T. Hence, the manufacturer sets the highest possible T^* ensuring that the supplier does not quit the development. Finally, it can happen that the manufacturer prefers the supplier to release the component without testing, as we know that after testing the supplier might very often prefer not to release the component due to potential losses. In this case, the manufacturer needs to lower T down to $\utilde{T}$ level to incentivize the supplier to release the component blindly.

4.4.4 Efficient Contract

As we could see, the residual claimant contract does not achieve the first-best outcome in our model since it allows for the exit option. In this section we construct a contract that would be able to achieve the first-best outcome and discuss its possible practical implications. We call this contract the efficient contract. The key to the construction of such a contract is that we need to extend the supplier liability for the exit option, i.e., for the case when the supplier decides not to release the component. In other words, the supplier needs to be obliged to pay a penalty T even if she does not release the component and quits the collaboration.

Proposition 4.5. *If $r_1 = R - S - T$ and $r_0 = L - l + T$, where $T < R - S$, and the supplier is obliged to pay $r_0' = T$ if she decides to quit the development after testing the component, then the first-best outcome is achieved. Furthermore,*

(i) the supplier's decision rule for testing the component is equivalent to (4.5) *for optimal T;*

(ii) the optimal manufacturer's portion of the profit is

$$T^* = \Big(1 - F(z)\Big)\mathrm{E}_{\theta \geq z}\{\theta(R-S) - (1-\theta)L\} - c \tag{4.17}$$

if (4.5) *holds, and* $T^* = \mathrm{E}_\theta\{\theta(R-S) - (1-\theta)L\}$ *otherwise.*

Proposition 4.5(ii) shows that the manufacturer does not only ensure the optimal level of testing but also appropriates the entire expected profit from the development of a new component leaving the supplier with zero expected profit.

Although this contract achieves the first-best outcome, it is hard to implement in practice due to the penalty charged from the supplier in case of her decision not to release the component. This penalty imposes too high risk on the supplier which, if we consider a long-term perspective, can lead to the supplier's bankruptcy or lower performance and thus hurt back the manufacturer for the potential future projects.

4.5 Model Extensions

4.5.1 Cost-Sharing in Reward Contract

The model can have several important extensions. First, we analyze the case when the manufacturer can subsidize the component testing and bear a portion $\phi \in [0,1]$ of the testing costs. Therefore, ϕ is the additional decision variable of the manufacturer, which potentially could induce the efficient testing level.

If the cost-sharing is allowed, the supplier will prefer testing when the following holds:

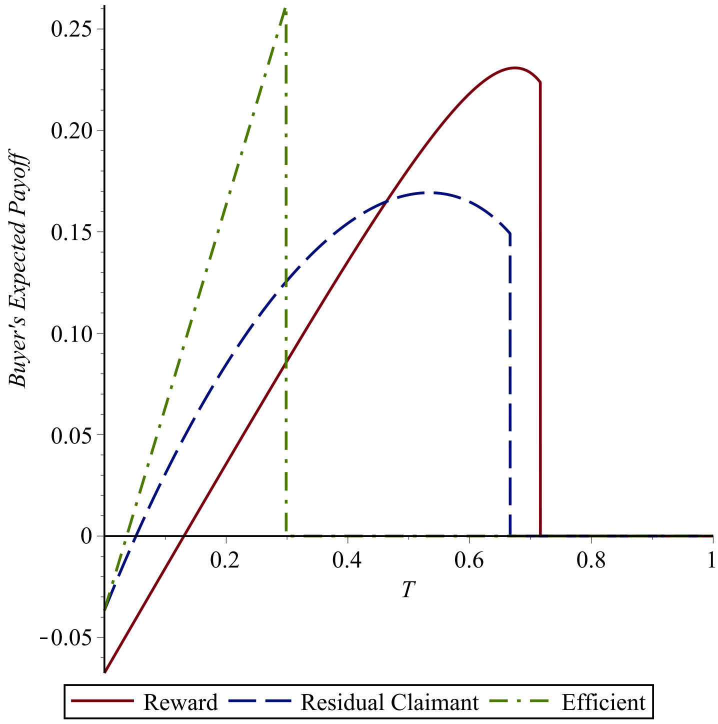
$$c(1-\phi) \leq \int_0^{\hat{z}} \Big((1-\theta)l - \theta(R-S) + \theta T\Big) f(\theta)\mathrm{d}\theta, \tag{4.18}$$

if $\mathrm{E}_\theta\{\theta(R-S-T)-(1-\theta)l\} \geq 0$, where $\hat{z} = \frac{l}{R-S+l-T}$. Recall that the right-hand side of (4.18) or, similarly, (4.9) is non-decreasing in T. It means that if (4.18) holds at $T = \underline{T}$, then $\phi^* = 0$, i.e., no cost subsidies are necessary since the supplier will test the component anyway. The same holds true if subsidies cannot induce testing, which is true if (4.9) does not hold at $T = \overline{T}|_{c=0}$. In other cases, subsidies can be applied to induce testing if the benefit from testing exceeds the subsidy value.

One could argue that a higher subsidy for testing may lead to a higher T even when the supplier does not need to switch from non-testing to testing, and optimally the manufacturer might need to compensate the testing costs fully and then compensate it with higher T. However, this intuition is not correct as the marginal loss from increasing subsidies is always higher than the marginal gain from increasing T. To see this, consider the manufacturer's payoff when the supplier chooses to test the component: $\pi_1 = -\phi c + \int_{\hat{z}}^{1}(T\theta - L(1-\theta))f(\theta)\mathrm{d}\theta$. The most important insight is that the optimal level of payment to the manufacturer if the supplier chooses to test the component is independent of c and equals T^* as defined in Section 4.4.2. More formally, the decision variables are separable and can be optimized independently of each other. Change in T^* is associated only with the supplier's decision to test or not to test. Therefore, the algorithm to find the optimal subsidy level is as follows. First, find the optimal T^* without subsidies. Then, if the supplier chooses to test under T^*, no subsidies are required. However, if the tests are not performed under T^* (and thus $T^* = \underline{T}$), find the optimal T_0^* assuming $c = 0$. If $T_0^* = \underline{T}$, then no subsidy is necessary. Otherwise, solve (4.18) as equality for ϕ at $T = T_0^*$. If π_1 at $T = T_0^*$ is greater than the optimal manufacturer's expected payoff under no-subsidy case, then the found ϕ is the optimal subsidy level.

4.5.2 Contract Comparison

An important question is how the manufacturer optimally chooses between residual claimant and reward contracts when the efficient contract option is unavailable. We provide a series of numerical examples to grasp the most important insights. The profit under the efficient contract is provided for reference. The manufacturer's payoff comparison of the three contract types is illustrated in Figure 4.2.



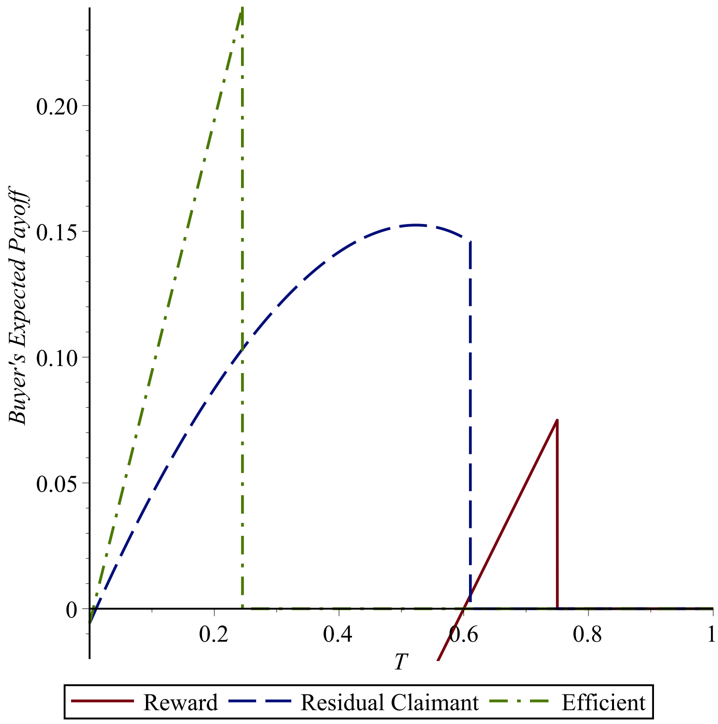
$$\theta \sim Beta(.5, .5), R = 1, S = .2, L = .3, l = .2, c = .02$$

FIGURE 4.2: The Manufacturer's Expected Payoff

As we can see, the intuitively appealing residual claimant contract in the way we defined it in 4.4.3 can be suboptimal to a simple reward contract without any penalties for the failure. Though counter-intuitive at the first sight, this effect has a logical explanation. As we could see from the analysis, the residual claimant contract makes the supplier "over-test" the component, i.e., test it even if the costs of testing are high relative to the potential rewards. This leads to the fact that the supplier is less motivated to participate in development at all, and she often chooses to quit after the tests are completed at zero additional cost and thus to avoid the risk of being penalized. For this reason, the manufacturer has to increase the supplier's reward in case of the component success, which leads to the lower expected payoff for the manufacturer.

The key reason for this inefficiency lies in the possibility for the supplier to quit the project after the component is tested. Being common practice, it, however, leads to both contract inefficiency and lower manufacturer's payoff. As we have discussed, the option to overcome this problem is to impose the efficient contract through installing a penalty from the supplier to quit the project.

However, this result is not generally true. In cases with a lower reputation loss for the supplier in case of failure and a higher losses for the manufacturer, the contract optimality can be reversed. Consider the example in Figure 4.3.

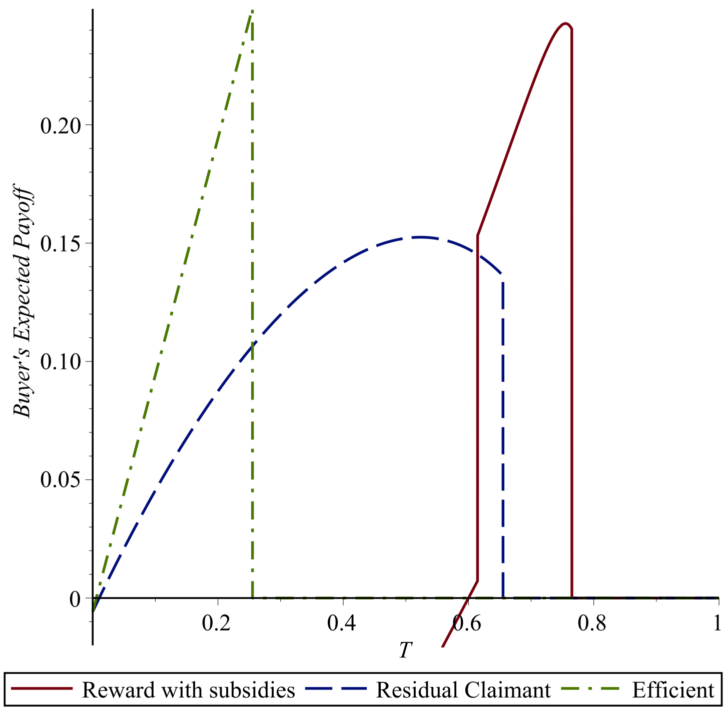


$$\theta \sim Beta(.5, .5), R = 1, S = .2, L = .6, l = .05, c = .02$$

FIGURE 4.3: The Manufacturer's Expected Payoff: Low l and High L

We can see that the contract assuming penalties for the component failure performs better than the purely reward-based contract. The primary reason is that with a low reputation loss, the supplier is not interested in performing the tests, as her expected payoff from the blind (no-testing) component release is sufficiently high. This strategy hurts the manufacturer especially strongly when the manufacturer's losses associated with the component failure are high. Similar effect will take place if the supplier is entitled to subsidies for the component development which she receives in case of the component adoption by the manufacturer.

Now let us consider the same set of parameters as in Figure 4.3, but we will allow for cost subsidies for the reward contract. The result is shown in Figure 4.4.



$$\theta \sim Beta(.5, .5), R = 1, S = .2, L = .6, l = .05, c = .02, \phi = .21$$

FIGURE 4.4: The Manufacturer's Expected Payoff: Subsidy Allowed

We can see that the manufacturer's expected payoff under the reward contract with the optimal subsidy level generates the outcome close to that under the efficient contract. Note that for this particular example, for illustrative purposes, we did not take the optimal ϕ under which the manufacturer's expected payoff would be even closer to that under the efficient contract and the corresponding graph would have a single spike at T^*.

4.5.3 Improvement Option

Another extension addresses the possibility for the supplier to improve the component after testing at additional cost. The supplier's problem is relatively simple: She decides whether to improve or not based on cost-benefit analysis of this option. The manufacturer can account for this option when finding the optimal T. However, for the manufacturer the issue is not that clear. Should the manufacturer subsidize the improvement given that he cannot observe the test results?

In particular, in some cases the supplier would improve the component without any subsidies, while in other cases the subsidies are essential to switch the supplier preference from component recommendation or quitting the project to component improvement. Another issue is whether the improvement subsidy should replace the test subsidy, or they can be complements.

From modeling perspective, the supplier bears improvement costs c_i and then stochastically improves θ by θ_i so that the new success probability becomes $\theta + \theta_i$, where the improvement value $\theta_i \in (0, 1-\theta)$ follows some known probability distribution, where subscript i stands for improvement. After the improvement value is realized, the supplier chooses to release the component or quit the project. We denote the expected probability of success after improvement as $\overline{\theta}(\theta)$ and assume that $\overline{\theta}(\theta)$ is non-decreasing in θ. The manufacturer needs to decide and announce whether he is ready to subsidize the component improvement and in which portion $\phi_i \in [0, 1]$ of improvement costs c_i.

The supplier chooses to invest in the component if $\theta \geq z_i$ where $z_i = \theta_i(\theta) - \frac{c_i}{R-S+l-T}$. If the condition does not hold, the supplier compares θ to $\hat{z} = z_c$ as before. Note that $z_i = z_c + \frac{(T-S-T)\theta_i(\theta)-l(1-\theta_i(\theta))-c_i}{R-S-T+l}$.

If T is sufficiently low, then $z_i > z_c$, which means that after testing the supplier chooses (a) to improve the component if $\theta \geq z_i$, (b) to release the component without improvement if $z_c \leq \theta < z_i$, and (c) to quit the collaboration if $\theta < z_c$. However, if T is sufficiently high, then $z_i < z_c$, in which case the supplier decides to improve the component if $\theta \geq z_i$ and to quit the collaboration otherwise, thus never releasing the component without improvement, which makes improvement subsidies from the manufacturer redundant for this case.

4.6 Conclusion

In this chapter, we have modeled the supplier's incentives to perform the component testing prior to its release to the manufacturer for the mass production. The simple contracts such as reward or residual claimant contract cannot ensure the efficient outcome leading to the component under- or over-testing by supplier, meaning that the supplier either does not perform the essential tests or performs them even when the cost of testing is excessive. However, neither case is eventually beneficial for the manufacturer.

Reward contract does not imply any penalties for the supplier in case of component failure apart for the reputation loss which supplier bears in case of failure under any contract type. The important insight for this contract type is that the value of component testing is decreasing in the reward the supplier receives in case of component success, and therefore with high reward the supplier is less prone to test the component. The intuition is that when the supplier's reward is relatively small, and thus comparable to the reputation losses in case of failure, the supplier prefers to test the component at higher testing costs as she needs to be sure that the component will work, or she quits the development process.

Residual claimant contract allows for penalties charged from the supplier in addition to her reputation loss in case of component failure. However, this contract is not able to achieve the efficient outcome and incentivizes the supplier to test the component even at prohibitively high cost. Surprisingly, this behavior does not benefit the manufacturer. Although performing testing more often than the manufacturer would do himself, the supplier does not choose to release the component often enough. Being loaded with penalties in case of failure, the supplier chooses to quit the development rather than to release the component, unless the success probability learned during tests is very high.

There exists an efficient contract that leads to the first-best outcome. However, it implies that the manufacturer should impose penalties on the supplier even if the latter prefers to quit the development after performing the tests. Essentially, the efficient contract will be the residual claimant contract with this additional penalty charge. However, this contract attributes all the risk to the supplier while the manufacturer extracts all the expected gain.

Chapter 5

Conclusion

This thesis is an attempt to provide solutions to some of the acute problems occurring due to incentive misalignment of the key component supplier and the new product manufacturer at the early stages of collaborative product development. We have considered three different scenarios of collaboration and the corresponding problems arising in its course. For each scenario we have constructed an analytical model capturing the specifics of each particular case. Further, by a means of non-cooperative game theory, we have analyzed the incentives of the involved parties and identified the possible avenues bridging their objectives.

The first essay deals with a target costing contract for alternative designs of the same component which are developed and tested sequentially. As supplier acquires private information about the mass production cost of components based on different designs, she can opportunistically manipulate the choice of the design for the mass production stage. We find that it is not necessarily optimal to set identical target costs for similar alternative designs (in terms of estimated component cost and performance at the mass production stage), and it is not necessarily optimal to set different target costs for dissimilar designs. Furthermore, we show that the timing of decisions is important, i.e., to set target costs up front (commitment scheme) or to announce each target cost only before a particular design development (flexible scheme). While intuitively the flexible scheme may be dominated since it aggravates the supplier's opportunistic behavior, under some circumstances the manufacturer can actually take advantage of the supplier's opportunistic behavior by carefully designing the flexible target costing scheme. Finally, we show that it is optimal to test alternative designs in increasing profit margin order if the testing cost per design is sufficiently low, which is in contrast to the literature suppressing the effect of the supplier opportunistic behavior.

The second essay addresses the incentive conflict problem when the manufacturer creates multiple parallel teams working on the same project. The crucial decision for the manufacturer is to allocate each team to one of the different potential suppliers of the key component in such a way that the suppliers exert sufficient effort for the component development. We find the equilibrium supplier effort levels as a function of team allocation between the suppliers under two admissible contracts: target costing and performance-contingent. Interestingly, we find that the expected effort level of a supplier might actually increase in the number of teams working with the competing supplier if there are synergies between the teams. It means that increasing competition (up to a reasonable level) can boost the supplier's effort levels and, consequently, the manufacturer's expected profit. Furthermore, we show that even in situations when one supplier dominates the other in the key characteristics, it might be optimal for the manufacturer to allocate at least one team to the worse supplier to induce the competition and benefit from the higher suppliers' efforts.

The third essay focuses on the mismatch in incentives with respect to testing the component prior to its adoption at the mass production stage. There exist multiple practical examples when the suppliers do not perform enough testing and the manufacturers lack expertise to perform and identify the required tests, which might result in component failure after the product is developed and marketed.

We investigate different admissible contracts between the manufacturer and the supplier and find that neither reward nor residual claimant contract can achieve the first-best outcome. The reason is that the supplier has an outside option to quit the project after the testing stage which makes residual payment non-applicable for all the possible outcomes. Surprisingly, although the residual claimant contract leads to a very high level of testing by the supplier, it does not benefit the manufacturer, as the supplier prefers not to release the component unless she is fully sure of its reliability. Further, we construct an efficient contract leading to the first-best supply chain profit. However, it implies penalties for the supplier even if she does not release the component and chooses to stop the development, which makes this contract hard to implement in practice. Hence, we focus our attention on analysis of how the manufacturer optimally chooses between reward or residual claimant contract. Finally, we investigate if manufacturer subsidies can lead to more testing and under which conditions the supplier would try to improve a component should she have such an opportunity.

Overall, the main insights from this thesis can be summarized as follows:

- The manufacturer can benefit from the opportunistic supplier behavior by carefully adjusting the target costing scheme. In particular, if the expected performance difference of alternative component designs is sufficiently high and their expected performance is sufficiently greater than their expected mass production cost, the manufacturer should deploy the flexible target costing scheme and start testing from the component designs with lower expected performance.

- Additional competition among suppliers through allocation of more internal teams to one of them can boost up the efforts of the other supplier and increase the manufacturer's expected profit. This effect holds if the total number of teams is sufficiently small and the supplier's synergy of working with multiple teams is sufficiently high. Furthermore, the manufacturer may find it optimal to allocate more teams to the supplier whose capabilities are dominated by the capabilities of another supplier.

- Standard reward and residual claimant contracts do not provide enough incentives for the supplier to perform the optimal testing of a component before its release for the mass production. To incentivize the supplier to perform sufficient component testing, the manufacturer may need to deploy a residual reward contract which penalizes the supplier even if she chooses not to release the component for mass production.

Appendix A

Supplement for Chapter 2

A.1 Proof of Lemma 2.1

(i) Suppose that $\exists\, t : u^C_{t+1}[\pi_{t+1}, v_{t+1}]$ increases in v_{t+1}. Then equation (2.1) implies $u^C_t[\pi_t, v_t]$ increases in v_t. Note that $u^C_{N+1}[\pi_{N+1}, v_{N+1}] \equiv v_{N+1}$ increases in v_{N+1}. By induction, $u^C_t[\pi_t, v_t]$ increases in v_t for all $t = 1, ..., N$. Similarly, we prove $u^F_t[\pi_t, v_t|\ W_t]$ increases in v_t given equation (2.2). Note that a change in v_t does not lead to a change in W_t for the F scheme because v_t cannot be observed by the manufacturer.

(ii) Recall that $\pi_t \in \{0, R_1 - w_1, ..., R_{t-1} - w_{t-1}\}$. Suppose $0 \leq R_1 - w_1 \leq ... \leq R_{t-1} - w_{t-1} ... \leq R_N - w_N$, then $\forall\ t' > t$, $\Pr(r_{t'} - w_{t'} > \pi_{t'})$ is invariant to $\pi_{t'}$. Now suppose $\exists\, t : u^C_{t+1}[\pi_{t+1}, v_{t+1}]$ is invariant to π_{t+1}, then given the above probability and equation (2.1), $u^C_t[\pi_t, v_t]$ is invariant to π_t. Since $u^C_{N+1}[\pi_{N+1}, v_{N+1}]$ is invariant to π_{N+1}, by induction $u^C_t[\pi_t, v_t]$ is invariant to π_t, $\forall\ t$.

Now suppose the opposite, i.e., $\exists\ t' > t : R_t - w_t > R_{t'} - w_{t'}$. First consider $\pi_{t'} \leq R_t - w_t$; as long as this condition holds, $\Pr(r_{t'} - w_{t'} > \pi_{t'})$ is constant in $\pi_{t'}$, and hence $u^C_{t'}[\pi_{t'}, v_{t'}]$ is constant for increasing $\pi_{t'}$. However, if $\pi_{t'}$ increases sufficiently, such that $\pi_{t'} > R_t - w_t$, then $\Pr(r_{t'} - w_{t'} > \pi_{t'}) = 0$, i.e., the probability of design t' to be accepted is dropping to zero if the dominated earlier design t was accepted by the supplier, and hence $u^C_{t'}[\pi_{t'}, v_{t'}]$ decreases in this case. Again for further increases of $\pi_{t'}$, $u^C_{t'}[\pi_{t'}, v_{t'}]$ is constant. Using similar induction logic as above, we show that $u^C_t[\pi_t, v_t]$ is non-increasing in π_t, $\forall\ t$.

A.2 Proof of Proposition 2.2

Denote the supplier profit-to-go function for period $t+1$ from equations (2.1) and (2.2) if the supplier rejects design t as $U_t^{C(0)}$ and $U_t^{F(0)}$, respectively, and if she accepts as $U_t^{C(2)}$ and $U_t^{F(2)}$, respectively. We omit superscripts C and F if the argument applies to both schemes. $U_t^{(0)}$ is invariant to c_t. Based on the result of Lemma 2.1(i), $U_t^{(2)}$ is monotonically decreasing in c_t. Therefore, there exists a unique $\bar{c}_t$ such that the supplier releases a design t if and only if $c_t \leq \bar{c}_t$. Note that if at some $c_t = x$, $U_t^{(0)} > (=)(<) U_t^{(2)}$ then $\bar{c}_t < (=)(>) x$.

Setting $U_N^{(0)} = U_N^{(2)}$ and solving for c_N, we obtain $\bar{c}_N = w_N - v_N$.

(i) For the C scheme, consider equation (2.1) at point $c_t = w_t - v_t$. Then, $U_t^{(0)} > (=)(<) U_t^{(2)}$ is equivalent to $u^C_{t+1}[\pi_t, v_t] > (=)(<) \alpha u^C_{t+1}[R_t - w_t, v_t] + (1-\alpha) u^C_{t+1}[\pi_t, v_t]$, or simplifying, $u^C_{t+1}[\pi_t, v_t] > (=)(<) u^C_{t+1}[R_t - w_t, v_t]$.

We claim that $U_t^{(0)} > U_t^{(2)}$ and hence $\bar{c}_t < v_t - w_t$ if $\exists\ t' > t : R_t - w_t > R_{t'} - w_{t'}$, $R_{t'} - w_{t'} \geq \pi_t$, and $\Pr(c_{t'} \leq \bar{c}_{t'}) > 0$. Note that since $\exists\ t' > t : R_t - w_t > R_{t'} - w_{t'} \geq \pi_t$, then $\Pr(r_{t'} - w_{t'} > \pi_{t'}) | (\pi_{t+1} = \pi_t) > 0$ (i.e., if design t is rejected, design t' can be accepted), and $\Pr(r_{t'} - w_{t'} > \pi_{t'}) | (\pi_{t+1} = R_t - w_t) = 0$ (i.e., if design t is accepted, design t' will be surely rejected). Given that $\Pr(c_{t'} \leq \bar{c}_{t'}) > 0$, $u^C_{t'+1}[\pi_t, v_t] > u^C_{t'+1}[R_t - w_t, v_t]$ from (2.1), which by induction leads to $u^C_{t+1}[\pi_t, v_t] > u^C_{t+1}[R_t - w_t, v_t]$, and hence $\bar{c}_t < v_t - w_t$.

Suppose that the above conditions do not hold. First, $\forall\, t' > t : R_t - w_t \leq R_{t'} - w_{t'}$. Then, $\Pr(r_{t'} - w_{t'} > \pi_{t'})$ is constant for all $\pi_{t'} \leq \max\{\pi_t, R_t - w_t\}$, i.e., for all future periods it does not make any difference for the acceptance probability if the current design is rejected or accepted. Therefore, $\forall\, t' > t : u^C_{t'}[\pi_t, v_{t'}] = u^C_{t'}[R_t - w_t, v_{t'}]$, and hence $u^C_{t+1}[\pi_t, v_t] = u^C_{t+1}[R_t - w_t, v_t]$, and $U^{(0)}_t = U^{(2)}_t$ and $\bar{c}_t = v_t - w_t$. Suppose that $R_{t'} - w_{t'} < \pi_t$. Then, design t' is always rejected by the manufacturer, i.e., $\Pr(r_{t'} - w_{t'} > \pi_{t'}) = 0$ and constant for all $\pi_{t'} \leq \max\{\pi_t, R_t - w_t\}$. Similarly, $U^{(0)}_t = U^{(2)}_t$ and hence $\bar{c}_t = v_t - w_t$. Suppose that $\Pr(c_{t'} \leq \bar{c}_{t'}) = 0$. Then, design t' is always rejected by the supplier. Similarly, $U^{(0)}_t = U^{(2)}_t$ and hence $\bar{c}_t = v_t - w_t$. Similar logic remains if any combination of the conditions does not hold.

(ii) The analysis of the F scheme is more complex due to adjustments in $W^{(i)}_{t+1}$, $i = \{0, 1, 2\}$. We say that $\widehat{W}_t$ dominates $\widetilde{W}_t$, denoted by $\widehat{W}_t > \widetilde{W}_t$, if $\hat{w}_i \geq \tilde{w}_i$ for all $\hat{w}_i \in \widehat{W}_t$ and $\tilde{w}_i \in \widetilde{W}_t$ with at least one strict inequality. We say that $u_t[\pi_t, v_t|\, W_t]$ is increasing (decreasing) in W_t if for any $\widehat{W}_t > (<) \widetilde{W}_t$, $u_t[\pi_t, v_t|\, \widehat{W}_t] > (<)\ u_t[\pi_t, v_t|\, \widetilde{W}_t]$. Similarly to the C scheme, consider equation (2.2) at point $c_t = w_t - v_t$:

$$u^F_t[\pi_t, v_t|\, W_t] = \max \begin{cases} U^{F(0)}_t = u^F_{t+1}[\pi_t, v_t|\, W^{(0)}_{t+1}], & \text{if rejects design } t; \\ U^{F(2)}_t = \Pr(r_t - w_t > \pi_t)\ u^F_{t+1}[r_t - w_t, v_t|\, W^{(2)}_{t+1}] & \\ + \Pr(r_t - w_t = \pi_t)\ u^F_{t+1}[\pi_t, v_t|\, W^{(0) \text{ or } (2)}_{t+1}] & \\ + \Pr(r_t - w_t < \pi_t)\ u^F_{t+1}[\pi_t, v_t|\, W^{(1)}_{t+1}], & \text{if accepts design } t, \end{cases} \tag{A.1}$$

When choosing whether to accept or reject design t, the supplier compares $u^F_{t+1}[\pi_t, v_t|\, W^{(0)}_{t+1}]$ with the weighted average of u^F_{t+1} if she releases the design. A sufficient condition for $U^{F(0)}_t > U^{F(2)}_t$ and hence $\bar{c}_t < w_t - v_t$ is that all the components of the weighted average are lower than $u^F_{t+1}[\pi_t, v_t|\, W^{(0)}_{t+1}]$. The above holds if (a) $u^F_t[\pi_t, v_t|\, W_t]$ is increasing in W_t, (b) $W^{(2)}_{t+1} < W^{(0)}_{t+1}$, and (c) $W^{(1)}_{t+1} \leq$

$W^{(0)}_{t+1}$. In words, if (a) the supplier benefits from higher W_t, (b) and (c) by releasing design t with $c_t = v_t - w_t$ the supplier makes W_t decrease, then $\overline{c}_t < w_t - v_t$. Note that if the supplier expects to get higher target costs following the design acceptance, then it might be that $\overline{c}_t = w_t - v_t$ or $\overline{c}_t > w_t - v_t$.

(a) Consider $u^F_N[\pi_N, v_N|\ W_N] = \max\{v_N, \Pr(r_N - w_N > \pi_N)(w_N - c_N) + \Pr(r_N - w_N \leq \pi_N)v_N\}$, which is strictly increasing in w_N as long as $w_N \leq R_N - \pi_N$, which is always true assuming profit maximizing manufacturer. The reason is that $\Pr(r_N - w_N > \pi_N)$ does not depend on w_N (and equals α) when $w_N \leq R_N - \pi_N$. Therefore, $u^F_N[\pi_N, v_N|\ W_N]$ is increasing in w_N for feasible w_N. Now suppose $\exists\ t : u^F_{t+1}[\pi_{t+1}, v_{t+1}|\ W_{t+1}]$ is increasing in w_{t+1}. Consider $u^F_t[\pi_t, v_t|\ W_t]$ from equation (2.2). Since $\Pr(r_t - w_t > \pi_t)$ does not depend on w_t for profit maximizing manufacturer, $u^F_t[\pi_t, v_t|\ W_t]$ is increasing in w_t for feasible w_t, from which we conclude that $u^F_t[\pi_t, v_t|\ W_t]$ is increasing in W_t, and therefore the property (a) is satisfied.

(b) For functional components, $W^{(2)}_{t+1} < W^{(0)}_{t+1}$ is trivially satisfied. Given constant R, the manufacturer always chooses to set lower W_{t+1} following a prototype acceptance, since any other policy will not increase the manufacturer's profit. The same logic is applicable for value-adding components if $R_t \geq R_{t'}$ for all $t' > t$.

(c) Intuitively, when the supplier rejects design t the manufacturer considers the true status-quo cost to be stochastically lower than when the supplier releases design t. Therefore, after design rejection the manufacturer offers a lower target cost rather than after design release. Formally, let $b^{(i)}_t$, $i = 0, 1, 2$ be the value of the manufacturer belief, which is a random variable with a distribution $B^{(i)}_{t+1}$ as defined by equations (A.24)—(A.26). Note that $b^{(1)}_{t+1} \geq_{fosd} b^{(0)}_{t+1}$, where FOSD stands for first-order stochastic dominance. We say that W_t is decreasing in b_t if $b'_t > b_t \Rightarrow W_t(b'_t) < W_t(b_t)$.

Next we show that W_t is decreasing in b_t which completes the proof of part (c). Consider the dynamic program describing the manufacturer profit, which is given by equation (2.5). The first-order condition to find the optimal payment for the manufacturer is

$$\begin{aligned}
&-\frac{\partial y^F_{t+1}[R_t - w_t, B^{(2)}_{t+1}]}{\partial w_t}\frac{A(w_t - w_k + b_t)}{a(w_t - w_k + b_t)} \\
&\quad = y^F_{t+1}[R_t - w_t, B^{(2)}_{t+1}] - y^F_{t+1}[\pi_t, B^{(1)}_{t+1}] + \frac{y^F_{t+1}[\pi_t, B^{(1)}_{t+1}] - y^F_{t+1}[\pi_t, B^{(0)}_{t+1}]}{\alpha} \qquad \text{(A.2)}
\end{aligned}$$

A sufficient condition for w_t to be decreasing in b_t is the following:

1. $\frac{\partial y^F_{t+1}[R_t - w_t, B^{(2)}_{t+1}]}{\partial w_t} < 0$. It follows from the fact that $y^F_t[\pi_t, B_t]$ is increasing in π_t. Proof by induction follows.

2. $\frac{A(w_t - w_k + b_t)}{a(w_t - w_k + b_t)}$ is increasing in $w_t - w_k + b_t$. It is satisfied since the cost distribution has a decreasing reversed hazard rate.

3. $y^F_t[\pi_t, B_t]$ is increasing in b_t. Proof by induction follows.

4. $B^{(2)}_{t+1}$ is independent of b_t. It is always satisfied by definition ($B^{(2)}_{t+1}$ reflects beliefs about c_t, while b_t is the belief about c_k).

5. $B^{(0)}_{t+1}$ and $B^{(1)}_{t+1}$ are non-decreasing in b_t. It follows from the Bayesian updating rule.

6. $\frac{\partial(y^F_{t+1}[\pi_t, B^{(1)}_{t+1}] - y^F_{t+1}[\pi_t, B^{(0)}_{t+1}])}{\partial b_t} < 0$, i.e., with higher belief, the further update upwards brings less value than with lower belief. From the definitions of $B^{(0)}_{t+1}$ and $B^{(1)}_{t+1}$, $\frac{\partial(b^{(1)}_{t+1} - b^{(0)}_{t+1})}{\partial b_t} < 0$. Therefore, the property is satisfied, since $y^F_t[\pi_t, B_t]$ is increasing in b_t (from property 3).

Under the above conditions, if b_t increases, the left-hand side of (A.2) increases while the right-hand side decreases. Therefore, w_t has to decrease to maintain the equality.

Proof by induction for parts 1 and 3. To see that $y_t^F[\pi_t, B_t]$ is increasing in π_t (b_t), suppose that $\exists\ t : y_{t+1}^F[\pi_{t+1}, B_{t+1}]$ is increasing in π_{t+1} (b_{t+1}). Then, from (2.5), $y_t^F[\pi_t, B_t]$ is increasing in π_t (b_t). Now consider $y_N^F[\pi_N, B_N]$:

$$\begin{aligned} y_N^F[\pi_N, B_N] &= \overline{A}(w_N - w_k + b_N)\pi_N + A(w_N - w_k + b_N)\Big(\alpha(R_N - w_N) + (1-\alpha)\pi_N\Big) \\ &= \pi_N + \alpha A(w_N - w_k + b_N)(R_N - w_N - \pi_N). \quad \text{(A.3)} \end{aligned}$$

From (A.3), we can see that $y_N^F[\pi_N, B_N]$ is increasing in π_N (b_N). Therefore, by induction $y_t^F[\pi_t, B_t]$ is increasing in π_t (b_t) for all t.

Now we show that $\bar{c}_t > w_t - v_t$ is possible if the above conditions are not satisfied, i.e., $\exists\ t' > t : R_{t'} > R_t$. The logic is as follows: Consider the design acceptance in period t such that $\pi_{t+1} = \pi_t + \epsilon$, and $c_t = w_t - v_t + \xi$, where $\epsilon \geq 0, \xi > 0$. Since $b_{t+1}^{(2)} <_{fosd} b_{t+1}^{(0)}$, then if ϵ is sufficiently small, $W_{t+1}^{(2)} > W_{t+1}^{(0)}$. Thus, if ξ is sufficiently small, $u_{t+1}^F[r_t - w_t, v_t - \xi|\ W_{t+1}^{(2)}] > u_{t+1}^F[\pi_t, v_t|\ W_{t+1}^{(0)}]$, i.e., the supplier prefers to accept at $c_t = w_t - v_t + \xi$, and $\bar{c}_t > w_t - v_t$.

A.3 General Framework for Propositions 2.3 and 2.4

The following applies to Proposition 2.3 when $R_1 = R_2 = R$ and to Proposition 2.4 when $R_1 \neq R_2$. For both schemes we derive the expressions for the supplier's thresholds, and the key is to show that under the optimal policy, $\bar{c}_1 = 0$ or $\bar{c}_1 = 1$. Then, we derive the feasible target cost policies which induce these threshold levels. Finally we provide the expressions for the manufacturer's profit, based on which, in parts A.3.1 and A.3.2, we compare the manufacturer's profit under these target cost policies.

- *C scheme.* It is straightforward that

$$\bar{c}_2 = \begin{cases} w_2 - w_1 + c_1, & \text{if 1 is accepted;} \\ w_2, & \text{otherwise.} \end{cases} \tag{A.4}$$

Consider $U_1^{(0)}$ and $U_1^{(1)}$, the supplier expected profit if she rejects or accepts the first design, respectively.

$$U_1^{(0)} = \alpha A(w_2)\mathbb{E}(w_2 - c \mid c \leq w_2) = \alpha \begin{cases} \beta w_2, & \text{if } 0 \leq w_2 < 1; \\ \beta w_2 + (1-\beta)(w_2 - 1), & \text{if } w_2 \geq 1. \end{cases} \tag{A.5}$$

$$U_1^{(1)} = (1-\alpha)U_1^{(0)} + \alpha \begin{cases} w_1 - c_1 + \alpha X, & \text{if } R_1 - w_1 \leq R_2 - w_2; \\ w_1 - c_1, & \text{if } R_1 - w_1 > R_2 - w_2, \end{cases} \tag{A.6}$$

where

$$\begin{aligned} X &= \Pr(w_2 - c_2 \geq w_1 - c_1)(w_2 - w_1 + c_1 - \mathbb{E}(c \mid c \leq w_2 - w_1 + c_1)) \\ &= \begin{cases} 0, & \text{if } w_2 - w_1 + c_1 < 0; \\ \beta(w_2 - w_1 + c_1), & \text{if } 0 \leq w_2 - w_1 + c_1 < 1; \\ \beta(w_2 - w_1 + c_1) + (1-\beta)(w_2 - w_1 + c_1 - 1), & \text{if } w_2 - w_1 + c_1 \geq 1. \end{cases} \end{aligned} \tag{A.7}$$

Now we find

$$
\begin{aligned}
\bar{c}_1 &= \arg_{c_1}\{U_1^{(1)} = U_1^{(0)}\} \\
&= \begin{cases} w_1, & \text{if } R_1 - w_1 \le R_2 - w_2; \\ \begin{cases} w_1 - \alpha\beta w_2, & \text{if } 0 \le w_2 < 1 \\ w_1 - \alpha(w_2 - 1 + \beta), & \text{if } w_2 \ge 1 \end{cases}, & \text{if } R_1 - w_1 > R_2 - w_2. \end{cases}
\end{aligned} \tag{A.8}
$$

Suppose that under some (w_1, w_2), it holds that $0 < \bar{c}_1 < 1$ or $\bar{c}_1 > 1$. Recall that c_1 follows a two-point distribution with a support $\{0, 1\}$. Then, according to (A.4) and (A.8), if $R_1 - w_1 \neq R_2 - w_2$, it is possible to reduce w_1 by some $\epsilon > 0$ so that the supplier probability of the first design release does not change and the same of the second design release does not decrease. If $R_1 - w_1 = R_2 - w_2$, it is possible to reduce both w_1 and w_2 by some $\xi > 0$ without affecting acceptance probabilities, unless $w_2 = 0$ or $w_2 = 1$. However, for $w_2 = 0$, it is always possible to reduce w_1 so that $\bar{c}_1 = 0$ or $\bar{c}_1 = 1$. For $w_2 = 1$, the manufacturer is always better off by changing the testing sequence so that the new $w_1 = 1$ and hence $\bar{c}_1 = 1$. Note that the latter always leads to increase in acceptance probability, which is straightforward for old $w_1 \ge 1$, and for old $w_1 < 1$ consider the change in acceptance probability (always beneficial for the manufacturer under equal margins from both prototypes) which is $1 - \beta - \Pr(c > \bar{c}_2)(1 - \beta) > 0$. Therefore, (w_1, w_2) can be optimal only if $\bar{c}_1 = 0$ or $\bar{c}_1 = 1$.

Suppose that under some (w_1, w_2), it holds that $\bar{c}_1 = 0$ or $\bar{c}_1 = 1$, and (i) $0 < w_2 < 1$ or (ii) $w_2 > 1$. It is always possible to reduce w_2 to (i) 0 or (ii) 1 without decreasing acceptance probabilities. Therefore, (w_1, w_2) can be optimal only if $w_2 = 0$ or $w_2 = 1$. Therefore, the admissible (w_1, w_2) are $(0, 0)$, $(1, 0)$, $(0, 1)$, $(\alpha\beta, 1)$, $(1, 1)$, and $(1 + \alpha\beta, 1)$. Note that $(0, 1)$ is applicable only for value-adding components if $R_1 \le R_2 - 1$, i.e., in the increasing sequence and high performance difference case. Similarly, $(1+\alpha\beta, 1)$ is applicable only for value-adding components if $R_1 - \alpha\beta > R_2$, i.e., in the decreasing sequence and high performance difference case.

The manufacturer's profit is given as

$$\pi_{w_1 w_2} = \begin{cases} \alpha \Pr(c \leq \bar{c}_1) \\ \Big(\big(1 - \alpha \Pr(c \leq \bar{c}_2)\big)(R_1 - w_1) + \alpha \Pr(c \leq \bar{c}_2)(R_2 - w_2)\Big) \\ +(1-\alpha) \Pr(c \leq \bar{c}_2)(R_2 - w_2), & \text{if } R_1 - w_1 \leq R_2 - w_2; \\ \alpha \Pr(c \leq \bar{c}_1)(R_1 - w_1) + (1-\alpha) \Pr(c \leq \bar{c}_2)(R_2 - w_2), & \text{if } R_1 - w_1 > R_2 - w_2. \end{cases} \tag{A.9}$$

- *F scheme.* Denote the second period target cost if the first design is accepted as $w_2^{(2)}$, and the same if rejected as $w_2^{(0)}$. Then,

$$\bar{c}_2 = \begin{cases} w_2^{(2)} - w_1 + c_1, & \text{if 1 is accepted;} \\ w_2^{(0)}, & \text{otherwise.} \end{cases} \tag{A.10}$$

From (A.10), we can see that the manufacturer can always reduce $w_2^{(2)}$ so that $\bar{c}_2 = 0$ or $\bar{c}_2 = 1$. Therefore, from the feasible realizations of c_1 and (A.10), $w_2^{(2)}$ can take only the following values: $w_2^{(2)} = w_1$, $w_2^{(2)} = w_1 - 1$ (for $w_1 \geq 1$), and $w_2^{(2)} = w_1 + 1$ (only for value adding case when $R_2 - R_1 \geq 1$, otherwise always rejected by the manufacturer).

We obtain $w_2^{(0)}$ from the manufacturer's profit for the last period as

$$w_2^{(0)} = \begin{cases} 0, & \text{if } \beta R_2 > R_2 - 1; \\ 1, & \text{otherwise.} \end{cases} \tag{A.11}$$

The supplier's expected profits from rejection and acceptance are

$$U_1^{(0)F} = \alpha A(w_2^{(0)})\mathbb{E}(w_2^{(0)} - c \mid c \leq w_2^{(0)}) = \begin{cases} 0, & \text{if } (1-\beta)R_2 < 1; \\ \alpha\beta, & (1-\beta)R_2 \geq 1. \end{cases} \tag{A.12}$$

$U_1^{(1)F}$ is identical to (A.6) and (A.7) where $w_2 \equiv w_2^{(2)}$. Solving for c_1, we obtain for the case $R_1 - w_1 \leq R_2 - w_2^{(2)}$:

$$\bar{c}_1 = \begin{cases} \begin{cases} w_1 + \frac{\alpha\beta}{1-\alpha} w_2^{(2)}, & \text{if } 0 \leq w_2^{(2)} < 1 - \alpha\beta \\ w_1 - \frac{\alpha}{1-\alpha}(w_2^{(2)} - 1 + \beta), & \text{if } w_2^{(2)} \geq 1 - \alpha\beta \end{cases}, & \text{if } (1-\beta)R_2 < 1, \\ \begin{cases} w_1 + \frac{\alpha\beta}{1-\alpha\beta}(w_2^{(2)} - 1), & \text{if } 0 \leq w_2^{(2)} < 1 \\ w_1 + \frac{\alpha}{1-\alpha}(w_2^{(2)} - 1), & \text{if } w_2^{(2)} \geq 1 \end{cases}, & \text{if } (1-\beta)R_2 \geq 1, \end{cases} \tag{A.13}$$

The same for the case $R_1 - w_1 > R_2 - w_2^{(2)}$ is given as:

$$\bar{c}_1 = \begin{cases} w_1, & \text{if } (1-\beta)R_2 < 1, \\ w_1 - \alpha\beta, & \text{if } (1-\beta)R_2 \geq 1, \end{cases} \tag{A.14}$$

The manufacturer can always reduce w_1 (and hence $w_2^{(2)}$) to such a level that $\bar{c}_1 = 1$ or $\bar{c}_1 = 0$. Note that the condition $R_1 - w_1 \leq R_2 - w_2^{(2)}$ does not raise a discontinuity concern, since $w_2^{(2)} \in \{w_1, w_1 - 1, w_1 + 1\}$, i.e., it changes linearly with w_1.

Finally, the manufacturer's profit is

$$\pi_{w_1F} = \begin{cases} \alpha \Pr(c \leq \bar{c}_1) \\ \Big(\big(1-\alpha \Pr(c \leq \bar{c}_2)\big)(R_1 - w_1) + \alpha \Pr(c \leq \bar{c}_2)(R_2 - w_2^{(2)})\Big) \\ +(1-\alpha)\Pr(c \leq \bar{c}_2)(R_2 - w_2^{(0)}), & \text{if } R_1 - w_1 \leq R_2 - w_2^{(2)}; \\ \alpha \Pr(c \leq \bar{c}_1)(R_1 - w_1) + (1-\alpha)\Pr(c \leq \bar{c}_2)(R_2 - w_2^{(0)}), & \text{if } R_1 - w_1 > R_2 - w_2^{(2)}. \end{cases} \tag{A.15}$$

A.3.1 Proof of Proposition 2.3

In parts A.3.1 and A.3.2, we denote the manufacturer's expected profit from policy (w_1, w_2) under the C scheme as $\pi_{w_1w_2}$ and under the F scheme as π_{w_1F}.

- *C scheme.* To ensure $\bar{c}_1 = 1$, we need to consider the following payment schemes (w_1, w_2): $(1,1)$ and $(1,0)$. For $\bar{c}_1 = 0$ to hold, the following schemes are possible: $(0,0)$ and $(\alpha\beta, 1)$, as given by equation (A.8).

Installing both payments to high cost level 1 leads to $\bar{c}_1 = 1$, and the manufacturer's profit is given as $\pi_{11} = \alpha(1-\beta)\Big((R-1)(1-\alpha\beta) + \alpha\beta(R-1)\Big) + \alpha\beta(R-1) + (1-\alpha)\alpha(R-1) = \alpha(2-\alpha)(R-1)$. Installing both payments to low cost level 0 leads to $\bar{c}_1 = \bar{c}_2 = 0$, and the manufacturer's profit is given as $\pi_{00} = \alpha\beta R + (1-\alpha\beta)\alpha\beta R = (2-\alpha\beta)\alpha\beta R$. Installing a decreasing payment scheme when $w_1 = 1$ and $w_2 = 0$ leads to $\bar{c}_1 = 1$, and the manufacturer's profit is given as $\pi_{10} = \alpha(1-\beta)\Big((R-1)(1-\alpha\beta) + \alpha\beta R\Big) + \alpha\beta(R-1) + (1-\alpha)\alpha\beta R = \alpha(1-\alpha\beta(1-\beta))(R-1) + \alpha\beta(1-\alpha\beta)R$. Comparing the potentially optimal profits, we find that $\pi_{11} \geq \pi_{10}$ if $R \geq \frac{(1-\alpha)(1-\beta(1-\beta))}{(1-\alpha)(1-\beta)}$, $\pi_{00} < \pi_{11}$ if $R > \frac{2-\alpha}{(1-\beta)(2-\alpha(1+\beta))}$, and $\pi_{10} \geq \pi_{00}$ if $R \geq \frac{1-\alpha+\alpha\beta(1-\beta)}{(1-\alpha)(1-\beta)}$. Defining $\underline{R} \equiv \min\left\{\frac{1-\alpha+\alpha\beta(1-\beta)}{(1-\alpha)(1-\beta)}, \frac{2-\alpha}{(1-\beta)(2-\alpha(1+\beta))}\right\}$, and $\overline{R} \equiv \max\left\{\frac{2-\alpha}{(1-\beta)(2-\alpha(1+\beta))}, \frac{1-\alpha(1-\beta(1-\beta))}{(1-\alpha)(1-\beta)}\right\}$, we have π_{00} dominating when $R < \underline{R}$, π_{10} dominating when $\underline{R} \leq R < \overline{R}$, and π_{11} when $R \geq \overline{R}$. Now consider $w_1 = \alpha\beta$ and $w_2 = 1$. Since $\pi_{(\alpha\beta)1} = \alpha\beta\Big(R - \alpha\beta\Big) + (1-\alpha\beta)\alpha(R-1) = \pi_{10}$, the manufacturer is indifferent between these policies.

- *F scheme.* Note that for functional components, (A.14) can never hold, since the manufacturer would never accept an equally performing component at a higher target cost.

Case 1. $(1-\beta)R \geq 1$. Equation (A.11) implies $w_2^{(0)} = 1$. From (A.10), the feasible $w_2^{(2)}$ are $w_2^{(2)} = w_1$ and $w_2^{(2)} = w_1 - 1$ (if $w_1 \geq 1$). From (A.13), we need to consider the following combinations of $(w_1, w_2^{(2)})$: $(\alpha\beta, \alpha\beta)$, and $(1+\alpha\beta, \alpha\beta)$.

Therefore, we consider the policies $w_1 = \alpha\beta$ and $w_1 = 1+\alpha\beta$, which lead to $\bar{c}_1 = 0$ and $\bar{c}_1 = 1$, respectively, and $w_2^{(2)} = \alpha\beta$ for either w_1. The manufacturer profit from the first strategy is given as $\pi_{(\alpha\beta)F} = \alpha\beta\Big(R - \alpha\beta\Big) + (1-\alpha\beta)\alpha(R-1) = \pi_{10} = \pi_{(\alpha\beta)1}$. Consider $\pi_{(1+\alpha\beta)F} = \alpha(1-\beta)\bigg(\Big(R - 1 - \alpha\beta\Big)(1-\alpha\beta) + \alpha\beta\Big(R - \alpha\beta\Big)\bigg) + \alpha\beta\Big(R - 1 - \alpha\beta\Big) + (1-\alpha)\alpha(R-1) = \alpha(1 - \alpha\beta(1-\beta))\Big(R - 1 - \alpha\beta\Big) + \alpha^2\beta(1-\beta)\Big(R - \alpha\beta\Big) + (1-\alpha)\alpha(R-1) < \pi_{11}$. Therefore, for Case 1, F scheme leads to the same profit for the manufacturer when $\underline{R} \leq R < \overline{R}$, but is inferior otherwise.

Case 2. $(1-\beta)R < 1$. From the case definition, $w_2^{(0)} = 0$. From (A.13), we need to consider the following policies $(w_1, w_2^{(2)})$: $(0,0)$ and $(1,0)$. The corresponding profit functions for the feasible policies will be identical to π_{00} and π_{10} in the C scheme. However, for $(1-\beta)R < 1$ (i.e. $R < \underline{R}^F$)), π_{10} is dominated by π_{00}.

A.3.2 Proof of Proposition 2.4

- *C scheme.* Recall that for value-adding components we additionally consider the testing sequence of the designs. Further we consider all the admissible policies established under the general framework in part C. In particular, we consider $(0,0)$, $(1,0)$, $(\alpha\beta, 1)$, and $(1,1)$. Recall that for high performance difference and increasing sequence we need to consider an additional policy, $(0,1)$. Similarly, for high performance difference and decreasing sequence — $(1+\alpha\beta, 1)$.

(A) Increasing performance, $R_1 < R_2$ (denoted as $\uparrow$). First we consider policies independent of performance difference. Consider $w_1 = w_2 = 0$, then $\bar{c}_1 = 0$, and $\pi_{00}^{\uparrow} = \alpha\beta\Big(R_L(1-\alpha\beta) + \alpha\beta R_H\Big) + (1-\alpha\beta)\alpha\beta R_H = \alpha\beta(1-\alpha\beta)R_L + \alpha\beta R_H$. If $w_1 = w_2 = 1$, then $\bar{c}_1 = 1$, and $\pi_{11}^{\uparrow} = \alpha\Big((1-\beta)\big((R_L-1)(1-\alpha) + \alpha(R_H - 1)\big) + \beta\big((R_L-1)(1-\alpha\beta) + \alpha\beta(R_H-1)\big)\Big) + (1-\alpha)\alpha(R_H-1) = \alpha(1-\alpha + \alpha\beta(1-\beta))(R_L-1) + \alpha(1-\alpha\beta(1-\beta))(R_H-1)$. The difference is $\pi_{11}^{\uparrow} - \pi_{00}^{\uparrow} = (1-\alpha)(1-\beta)R_L + (1-\beta)(1+\alpha\beta))R_H - 2$.

If $w_1 = 1$ and $w_2 = 0$, then $\bar{c}_1 = 1$, and $\pi_{10}^{\uparrow} = \alpha\Big((1-\beta)\big((R_L-1)(1-\alpha\beta) + \alpha\beta R_H\big) + \beta(R_L-1)\Big) + (1-\alpha)\alpha\beta R_H = \alpha(1-\alpha\beta(1-\beta))(R_L-1) + \alpha\beta(1-\alpha\beta)R_H$.

Now we turn to the policies dependent on performance difference. *Case 1.* Low performance difference, $R_H - 1 < R_L$. Consider the intermediate payment $w_1 = \alpha\beta$ and $w_2 = 1$, which ensures $\bar{c}_1 = 0$. $\pi_{(\alpha\beta)1}^{\uparrow 1} = \alpha\beta\big((R_L - \alpha\beta)(1-\alpha\beta) + \alpha\beta(R_H - 1)\big) + (1-\alpha\beta)\alpha(R_H-1) = \alpha\beta(1-\alpha\beta)(R_L-\alpha\beta) + \alpha(1-\alpha\beta(1-\beta))(R_H-1)$.

Case 2. High performance difference, $R_H - 1 \geq R_L$. With $w_1 = 0$ and $w_2 = 1$, the profit is $\pi_{01}^{\uparrow 2} = \alpha\beta\big(R_L(1-\alpha) + \alpha(R_H-1)\big) + (1-\alpha\beta)\alpha(R_H-1) = \alpha\beta(1-\alpha)R_L + \alpha(R_H-1)$.

(B) Decreasing performance, $R_1 > R_2$ (denoted as $\downarrow$). Again, we start with policies independent of performance difference. Consider $\pi_{00}^{\downarrow} = \alpha\beta R_H + (1-\alpha\beta)\alpha\beta R_L = \pi_{00}^{\uparrow}$. For the case of $w_1 = w_2 = 1$, $1 > \bar{c}_1 \geq 0$, and therefore this policy is not optimal.

Now we turn to policies dependent on performance difference. *Case 1.* Low performance difference, $R_H - 1 < R_L$. Let $w_1 = 1$ and $w_2 = 0$, which ensures $\bar{c}_1 = 1$. $\pi_{10}^{\downarrow 1} = \alpha\Big((1-\beta)\big((R_H-1)(1-\alpha\beta) + \alpha\beta R_L\big) + \beta(R_H-1)\Big) + (1-\alpha)\alpha\beta R_L = \alpha(1-\alpha\beta(1-\beta))(R_H-1) + \alpha\beta(1-\alpha\beta)R_L$.

Comparison with increasing performance for Case 1. Note that $\pi_{10}^{\downarrow 1} > \pi_{01}^{\uparrow 1}$ and $\pi_{10}^{\downarrow 1} > \pi_{(\alpha\beta)1}^{\uparrow 1}$. $\pi_{10}^{\downarrow 1}$ can be higher or lower than $\pi_{11}^{\uparrow}$ and $\pi_{00}^{\uparrow}$. It is higher if and only if two conditions hold: $R_L < \frac{1-\alpha+\alpha\beta(1-\beta)}{(1-\alpha)(1-\beta)}$ and $R_H > \frac{1-\alpha\beta(1-\beta)}{(1-\beta)(1-\alpha\beta)}$.

Case 2. High performance difference, $R_H - 1 \geq R_L$. If $w_1 = 1$ and $w_2 = 0$, $\pi_{10}^{\downarrow 2} = \alpha(R_H - 1) + (1-\alpha)\alpha\beta R_L$.

In this case, $R_H - \alpha\beta \geq R_L$, and therefore we need to consider $\pi_{(1+\alpha\beta)1}^{\downarrow 2} = \alpha(R_H - 1 - \alpha\beta) + (1-\alpha)\alpha(R_L - 1)$.

Finally, consider the policy $w_1 = \alpha\beta$ and $w_2 = 1$, which ensures $\bar{c}_1 = 0$. $\pi_{(\alpha\beta)1}^{\downarrow} = \alpha\beta(R_H - \alpha\beta) + (1-\alpha\beta)\alpha(R_L - 1) = \alpha\beta(R_H - \alpha\beta) + (1-\alpha\beta)\alpha(R_L - 1)$.

Comparison with increasing performance for Case 2. Consider $\pi_{00}^{\uparrow} - \pi_{10}^{\downarrow 2} = \Big(1 - (1-\beta)R_H + \alpha\beta(1-\beta)R_L\Big)\alpha$. Therefore, $\pi_{10}^{\downarrow 2}$ is optimal if $(1-\beta)(R_H - \alpha\beta R_L) \geq 1$.

Note that $\pi_{10}^{\downarrow 2} - \pi_{10}^{\uparrow} = \alpha(1 - \beta(1-\alpha\beta))(R_H - R_L) - \alpha^2\beta(1-\beta) > 0$. Consider $\pi_{10}^{\downarrow 2} - \pi_{(\alpha\beta)1}^{\downarrow} = \pi_{01}^{\uparrow 2} - \pi_{(\alpha\beta)1}^{\downarrow} = (1-\beta)(R_H - R_L - \alpha\beta) > 0$. Furthermore, $\pi_{(1+\alpha\beta)1}^{\downarrow 2} > \pi_{10}^{\downarrow 2}$ if $(1-\beta)R_L \geq 1 + \frac{\alpha\beta}{1-\alpha}$, which is satisfied if $(1-\beta)R_L \geq 1$, and hence if $(1-\beta)R_H \geq 1$ (this case, subcase 2.2, is considered in the proof for the F scheme below).

Conclusion for the C scheme: The profit functions generated by the non-dominated policies are $\pi_{00}^{\uparrow}$, $\pi_{11}^{\uparrow}$, $\pi_{10}^{\downarrow 2}$, $\pi_{01}^{\uparrow 2}$, and $\pi_{(1+\alpha\beta)1}^{\downarrow 2}$. In the proof for the F scheme below, we will find that $\pi_{(1+\alpha\beta)1}^{\downarrow 2}$ is dominated by $\pi_{(1-\alpha)F}^{\uparrow 2.2}$.

- *F scheme.* (A) Increasing performance $R_1 < R_2$. *Case 1.* $(1-\beta)R_H < 1$. It means $w_2^{(0)} = 0$. We need to consider the following combinations of $(w_1, w_2^{(2)})$ as prescribed by (A.13) and (A.14): $(0,0)$, and $(1,0)$. For $(0,0)$, the profit is identical to $\pi_{00}^{\uparrow}$. For $(1,0)$, the profit is identical to $\pi_{10}^{\uparrow}$.

Case 2. $(1-\beta)R_H \geq 1$. It means $w_2^{(0)} = 1$. *Subcase 2.1.* Low performance difference, $R_H - 1 < R_L$. In this subcase $w_2^{(2)} \leq w_1$. We need to consider the following combinations of $(w_1, w_2^{(2)})$ as prescribed by (A.13) and (A.14): $(\alpha\beta, \alpha\beta)$, and $(1+\alpha\beta, \alpha\beta)$. Then, $\pi^{\uparrow 2.1}_{(\alpha\beta)F} = \alpha\beta\Big((R_L - \alpha\beta)(1-\alpha\beta) + \alpha\beta(R_H - \alpha\beta)\Big) + (1-\alpha\beta)\alpha(R_H - 1)$, which is equal to $\pi^{\downarrow 1}_{10}$ from the C scheme. And $\pi^{\uparrow 2.1}_{(1+\alpha\beta)F} = \alpha\Big((R_L - 1 - \alpha\beta)(1-\alpha) + \alpha(R_H - \alpha\beta)\Big) + (1-\alpha)\alpha(R_H - 1)$, which is dominated by $\pi^{\downarrow 2}_{10}$ from the C scheme.

Subcase 2.2. High performance difference, $R_H - 1 \geq R_L$. In this subcase $w_2^{(2)} \geq w_1$. Therefore, we need to consider the following combinations of $(w_1, w_2^{(2)})$: $(\alpha\beta, \alpha\beta)$, $(0, 1)$, and $(1-\alpha), (2-\alpha)$. Note that the analysis of $(\alpha\beta, \alpha\beta)$ is identical to the Subcase 2.1 above.

Then, $\pi^{\uparrow 2.2}_{0F} = \alpha\beta\Big(R_L(1-\alpha) + \alpha(R_H - 1)\Big) + (1-\alpha\beta)\alpha(R_H - 1) = \alpha\beta(1-\alpha)R_L + \alpha(R_H - 1) = \pi^{\uparrow 2}_{01}$. If $w_1 = 1$, then $w_2^{(2)} = w_2^{(0)} = 1$ and the profit is identical to $\pi^{\uparrow}_{11}$.

$\pi^{\uparrow 2.2}_{(1-\alpha)F} = \alpha((1-\alpha)(R_L - (1-\alpha)) + \alpha(R_H - (2-\alpha))) + (1-\alpha)\alpha(R_H - 1)$. Now we compare it to the optimal C scheme policies. We verify the following: (a) $\pi^{\uparrow 2.2}_{(1-\alpha)F} \geq \pi^{\uparrow}_{11}$, (b) $\pi^{\uparrow 2.2}_{(1-\alpha)F} \geq \pi^{\downarrow 2}_{(1+\alpha\beta)1}$, (c) $\pi^{\uparrow 2.2}_{(1-\alpha)F} \geq \pi^{\uparrow 2}_{01}$, and (d) $\pi^{\uparrow 2}_{(1-\alpha)F} \geq \pi^{\uparrow}_{00}$. Note that (b) is always satisfied as $\pi^{\uparrow 2.2}_{(1-\alpha)F} - \pi^{\downarrow 2}_{(1+\alpha\beta)1} = \alpha^2\beta > 0$. Solving the system of inequalities, we can see that $\pi^{\uparrow 2.2}_{(1-\alpha)F}$ dominates the C scheme policies if $(1-\beta)R_H + (1-\alpha(1+\beta))R_L \geq 2-\alpha$. Note that $\bar{c}_1 = 1$ and $\bar{c}_2 = 1$ for this subcase, which completes *the proof of Corollary 1.*

(B) Case $R_1 > R_2$. *Case 1.* $(1-\beta)R_L < 1$. It means $w_2^{(0)} = 0$. Then $\bar{c}_1 = w_1$ from (A.14) if $R_H - w_1 > R_L - w_2^{(2)}$, and otherwise the thresholds are prescribed by (A.13). Therefore, two policies are feasible: $(0, 0)$ and $(1, 0)$. If $w_1 = 0$, then manufacturer's profit is identical to $\pi^{\downarrow}_{00}$. If $w_1 = 1$, then it is identical to $\pi^{\downarrow}_{10}$.

Case 2. $(1-\beta)R_L \geq 1$. It means $w_2^{(0)} = 1$. Then, $\bar{c}_1 = w_1 - \alpha\beta$ from (A.14) if $R_H - w_1 > R_L - w_2^{(2)}$, and otherwise the thresholds are prescribed by (A.13). Note that $w_2^{(2)} = w_1 + 1$ is not feasible for this case, as the manufacturer never accepts R_L instead of R_H at a higher target cost.*Subcase 2.1.* $R_H - 1 < R_L$. Then, the admissible policy is $(1, 0)$. The manufacturer's profit for $w_1 = 1$ is given as

$\pi_{1F}^{\downarrow 2.1} = \alpha\beta\Big((R_H - 1)(1-\alpha\beta) + \alpha\beta R_L\Big) + (1-\alpha\beta)\alpha(R_L - 1) = \alpha\beta(1-\alpha\beta)(R_H - 1) + \alpha^2\beta^2 R_L + \alpha(1-\alpha\beta)(R_L - 1)$, which is dominated by $\pi_{10}^{\downarrow}$.

Subcase 2.2. $R_H - 1 \geq R_L$. The only admissible policy is again $(1, 0)$, and the manufacturer's profit is $\pi_{1F}^{\downarrow 2.2} = \alpha\beta(R_H - 1) + (1-\alpha\beta)\alpha(R_L - 1)$, which is dominated by $\pi_{11}^{\uparrow}$.

Conclusion for the F scheme. The only strategy strictly dominating the others (including those from the C scheme) is $\pi_{(1-\alpha)F}^{\uparrow 2.2}$.

A.4 Proof of Corollary 2.5.

Refer to part A.3.2, F scheme, (A) Increasing performance, subcase 2.2.

A.5 Proof of Corollary 2.6.

From the profit comparison for the C and F schemes we can easily see that the optimal policies satisfy $R_1 - w_1 < R_2 - w_2$ for the C scheme and $R_1 < R_2$ for the F scheme.

A.6 Proof of Proposition 2.7

Following a similar logic as for the sequential case, we construct the supplier thresholds for both designs. Note that we do not have the time dimension, and therefore we replace the digital indices 1 and 2 with indices L and H for designs with performance of R_L and R_H, respectively. We start with characterizing the supplier's expected profit if she rejects ($U^{(0)}$) or accepts ($U^{(1)}$) prototype L (with symmetric results for H):

$$U_L^{(0)} = \begin{cases} \alpha w_H, & \text{if } c_H = 0; \\ \alpha(w_H - 1), & \text{if } c_H = 1 \text{ and } w_H \geq 1; \\ 0, & \text{otherwise}; \end{cases} \tag{A.16}$$

$$\begin{aligned} U_L^{(1)} &= (1-\alpha)U_L^{(0)} \\ &+ \alpha \begin{cases} w_L - c_L, & \text{if } R_L - w_L > R_H - w_H; \\ \begin{cases} \alpha w_H + (1-\alpha)(w_L - c_L), & \text{if } c_H = 0 \\ \alpha(w_H - 1) + (1-\alpha)(w_L - c_L), & \text{if } c_H = 1 \end{cases}, & \text{if } R_L - w_L \leq R_H - w_H. \end{cases} \end{aligned} \tag{A.17}$$

From (A.16) and (A.17), we find the supplier's acceptance threshold for prototype L:

$$\bar{c}_L = \begin{cases} w_L, & \text{if } R_L - w_L \leq R_H - w_H \text{ or } w_L - c_L \geq w_H - c_H; \\ \begin{cases} w_L - \alpha w_H, & \text{if } 0 \leq w_H < 1 \\ w_L - \alpha(w_H - 1), & \text{if } w_H \geq 1 \end{cases}, & \text{if } R_L - w_L > R_H - w_H \text{ and } w_L - c_L < w_H - c_H. \end{cases} \tag{A.18}$$

$\bar{c}_H$ is symmetric, i.e., all the indices should be changed from L to H and vice versa. Note that each threshold takes three different forms depending on the realization of c_L and c_H, i.e., if $c_H = c_L$, $c_H = 1$ and $c_L = 0$, or $c_H = 0$ and $c_L = 1$.

From the threshold structure, it follows that in optimality at least one of the following holds: either $w_L = \bar{c}_L \in \{0, 1\}$ or $w_H = \bar{c}_H \in \{0, 1\}$. The intuition behind it is straightforward: either $R_L - w_L \leq R_H - w_H$ or $R_H - w_H \leq R_L - w_L$ must hold, which means that either $w_L = \bar{c}_L$ or $w_H = \bar{c}_H$. Therefore, one can always reduce w_L or w_H to 0 or 1 without affecting the supplier's acceptance thresholds.

Therefore, the optimal strategy can contain only four possible cases: $w_L = \overline{c}_L = 1$, $w_L = \overline{c}_L = 0$, $w_H = \overline{c}_H = 1$, and $w_H = \overline{c}_H = 0$, which are presented in Table A.1. The optimal target cost and the corresponding thresholds for each of the case is obtained from (A.18) and the symmetric equation for $\overline{c}_H$, three conditions of which correspond to three lines for each of the four cases. We refer to this set of target costing policies as the potentially optimal policies for parallel prototyping. The *Condition* column in Table A.1 means that a policy is optimal for parallel prototyping only if the corresponding condition is satisfied, as obtained from (A.18). Ω indicates that a policy can be optimal for all parameter configurations. In the column of *F components*, the profits for each potentially optimal policy for functional components for parallel prototyping is compared against the profits for the optimal policies for functional components for sequential prototyping. In the column of *VA components*, we provide the same analysis for value-adding components with segregation for low and high performance difference components.

The list of the manufacturer's profits $\pi^{||}(w_L, w_H)$ for the potentially optimal policies for parallel prototyping is provided below. Let $\pi_L \equiv \alpha(R_L - w_L)$, $\pi_H \equiv \alpha(R_H - w_H)$, $\pi_{HL} \equiv \pi_H + (1-\alpha)\pi_L$, and $\pi_{LH} \equiv \pi_L + (1-\alpha)\pi_H$. The notation stands for the manufacturer's profits, if he receives only component L, only component H, both components but component H margin is higher, and both components but component L margin is higher, respectively. Denote the vector of potential cost realizations as $\boldsymbol{\beta} = (\beta^2, (1-\beta)\beta, \beta(1-\beta), (1-\beta)^2)$. It stands for four potential cost realizations: $c_L = c_H = 0$; $c_L = 1, c_H = 0$; $c_L = 0, c_H = 1$; and $c_L = c_H = 1$. Then the profits are as follows:

$\pi^{||}(1, 1 + R_H - R_L) = \boldsymbol{\beta}^T \times (\pi_{HL}, \pi_{HL}, \pi_{HL}, \pi_{HL})$,

$\pi^{||}(1, \alpha) = \boldsymbol{\beta}^T \times (\pi_{HL}, \pi_H, \pi_L, \pi_L)$,

<table>
<tr><th>w_L</th><th>$\bar{c}_L$</th><th>w_H</th><th>$\bar{c}_H$</th><th>Condition</th><th>F components</th><th colspan="2">VA components</th></tr>
<tr><th></th><th></th><th></th><th></th><th></th><th></th><th>$R_H - R_L < 1$</th><th>$R_H - R_L \geq 1$</th></tr>
<tr><td rowspan="3" colspan="2">1</td><td>$1 + R_H - R_L$</td><td>w_H</td><td>Ω</td><td>$= \pi_{11}$</td><td colspan="2">$< \pi_{11}^{\downarrow}$</td></tr>
<tr><td>α</td><td>0</td><td>Ω</td><td>$< \pi_{(\alpha\beta)1}$</td><td colspan="2">$< \pi_{(\alpha\beta)1}^{\downarrow}$</td></tr>
<tr><td>$1 + \alpha$</td><td>1</td><td>$R_H - R_L > \alpha$</td><td>N/A</td><td>$< \pi_{11}^{\downarrow}$</td><td>$< \pi_{(1+\alpha\beta)1}^{\downarrow 2}$</td></tr>
<tr><td rowspan="3" colspan="2">0</td><td>$R_H - R_L$</td><td>w_H</td><td>Ω</td><td>$= \pi_{00}$</td><td>$< \pi_{00}^{\downarrow}$</td><td>$\leq \pi_{10}^{\downarrow 2}$</td></tr>
<tr><td>0</td><td>0</td><td>Ω</td><td>$= \pi_{00}$</td><td colspan="2">$= \pi_{00}^{\downarrow}$</td></tr>
<tr><td>1</td><td>1</td><td>Ω</td><td>$< \pi_{10}$</td><td>$< \pi_{10}^{\downarrow 1}$</td><td>$= \pi_{10}^{\downarrow 2}$</td></tr>
<tr><td>$1 + R_L - R_H$</td><td>w_L</td><td rowspan="3" colspan="2">1</td><td>$R_H - R_L \leq 1$</td><td>$= \pi_{11}$</td><td>$< \pi_{10}^{\downarrow 1}$</td><td>N/A</td></tr>
<tr><td>α</td><td>0</td><td>Ω</td><td>$< \pi_{(\alpha\beta)1}$</td><td colspan="2">$< \pi_{10}^{\downarrow 1}$</td></tr>
<tr><td>$1 + \alpha$</td><td>1</td><td>$\varnothing$</td><td>N/A</td><td colspan="2">N/A</td></tr>
<tr><td>$R_L - R_H$</td><td>w_L</td><td rowspan="3" colspan="2">0</td><td>$\varnothing$</td><td>N/A</td><td colspan="2">N/A</td></tr>
<tr><td>0</td><td>0</td><td>Ω</td><td>$= \pi_{00}$</td><td colspan="2">$= \pi_{00}^{\downarrow}$</td></tr>
<tr><td>1</td><td>1</td><td>$\varnothing$</td><td>N/A</td><td colspan="2">N/A</td></tr>
</table>

N/A — a policy is not optimal under parallel prototyping case.

Table A.1: Optimal Target Cost Scheme for Parallel Prototyping

$$\pi^{||}(1, 1+\alpha) = \boldsymbol{\beta}^T \times (\pi_{HL}, \pi_{HL}, \pi_{HL}, \pi_{HL}), \text{ if } R_H - R_L > \alpha,$$

$$\pi^{||}(0, R_H - R_L) = \boldsymbol{\beta}^T \times \begin{cases} (\pi_{HL}, \pi_H, \pi_{HL}, \pi_H), & \text{if } R_H - R_L \geq 1 \\ (\pi_{LH}, \pi_H, \pi_L, 0), & \text{if } R_H - R_L < 1 \end{cases},$$

$$\pi^{||}(0, 0) = \boldsymbol{\beta}^T \times (\pi_{HL}, \pi_L, \pi_H, 0),$$

$$\pi^{||}(0, 1) = \boldsymbol{\beta}^T \times \begin{cases} (\pi_{HL}, \pi_{HL}, \pi_H, \pi_H), & \text{if } R_H - R_L \geq 1 \\ (\pi_H, \pi_{LH}, \pi_H, \pi_H), & \text{if } R_H - R_L < 1 \end{cases},$$

$$\pi^{||}(1 + R_L - R_H, 1) = \boldsymbol{\beta}^T \times (\pi_{HL}, \pi_H, \pi_{HL}, \pi_H), \text{ if } R_H - R_L \leq 1,$$

$$\pi^{||}(\alpha, 1) = \boldsymbol{\beta}^T \times \begin{cases} (\pi_{HL}, \pi_H, \pi_{HL}, \pi_H), & \text{if } R_H - R_L \geq 1 - \alpha \\ (\pi_{LH}, \pi_H, \pi_L, \pi_H), & \text{if } R_H - R_L < 1 - \alpha \end{cases},$$

where superscript T means transposed. The result of the comparison for each of these policies with the optimal C scheme policies for sequential prototyping is presented in Table A.1.

We can see that the optimal C scheme policies under sequential prototyping weakly dominate the optimal policies under parallel prototyping. For example, $\pi^{||}(1, 1 + R_H - R_L) = \pi_{11}$ for functional components and $\pi^{||}(1, 1 + R_H - R_L) < \pi^{\downarrow}_{11}$ for value-adding components.

A.6.1 Costly Prototyping

We will show that for costly prototyping under both C and F schemes $\bar{c}_{1c}$ and $\bar{c}_{2c}$ for any given policy are not greater than the respective thresholds for costless prototyping, $\bar{c}_1$ and $\bar{c}_2$. It means that any target costing policy for costless prototyping weakly dominates the same policy under costly prototyping. Therefore, if an optimal policy for costless prototyping leads to the same $\bar{c}_{1c}$ and $\bar{c}_{2c}$ and thus the same profit level under costly prototyping, this policy is also optimal for costly prototyping. Finally, we will derive the conditions under which all the optimal policies for high performance difference components for costless prototyping — which are $(0, 0)$ and $(0, 1)$ for the C scheme and $w_1 = 1 - \alpha$, $w_2^{(1)} = 2 - \alpha$, and $w_2^{(0)} = 1$ for the F scheme — are optimal for costly prototyping.

C scheme. $\bar{c}_{2c} = \bar{c}_2$ as defined by (A.4). The supplier expected profit if she rejects $(U_{1c}^{(0)})$ or accepts $(U_{1c}^{(1)})$ the design will be as follows.

$$U_{1c}^{(0)} = \alpha \begin{cases} \beta w_2, & \text{if } 0 \leq w_2 < 1 \text{ and } \alpha\beta(R_2 - w_2) \geq M; \\ \beta w_2 + (1 - \beta)(w_2 - 1), & \text{if } w_2 \geq 1 \text{ and } \alpha(R_2 - w_2) \geq M; \\ 0, & \text{otherwise.} \end{cases} \tag{A.19}$$

$$U_{1c}^{(1)} = (1-\alpha)U_{1c}^{(0)}$$
$$+\alpha \begin{cases} w_1 - c_1 + \alpha X, & \text{if } \alpha \mathbb{E}_{c_1 \le \bar{c}_1} \Pr\{w_2 - c_2 \ge w_1 - c_1\}(R_2 - w_2) - M \ge R_1 - w_1; \\ w_1 - c_1, & \text{otherwise}; \end{cases}, \tag{A.20}$$

where X is as defined by (A.7) and

$$\mathbb{E}_{c_1 \le \bar{c}_1} \Pr\{w_2 - c_2 \ge w_1 - c_1\}$$
$$= \begin{cases} \begin{cases} 0, & \text{if } w_2 - w_1 < 0 \\ \beta, & \text{if } 0 \le w_2 - w_1 < 1 \\ 1, & \text{if } w_2 - w_1 \ge 1 \end{cases}, & \text{if } 0 \le \bar{c}_{1c} < 1; \\ \begin{cases} 0, & \text{if } w_2 - w_1 < -1 \\ (1-\beta)\beta, & \text{if } -1 \le w_2 - w_1 < 0 \\ 1-(1-\beta)\beta, & \text{if } 0 \le w_2 - w_1 < 1 \\ 1, & \text{if } w_2 - w_1 \ge 1 \end{cases}, & \text{if } \bar{c}_{1c} \ge 1. \end{cases} \tag{A.21}$$

We can see that the supplier's profit in case of acceptance as defined by (A.20) is equal to or less than the respective profit as defined by (A.6) for any given w_1 and w_2. $U_{1c}^{(1)}$ is not greater than the respective measure for costless prototyping and $U_{1c}^{(0)}$ is the same for any given w_1 and w_2. It means that $\bar{c}_{1c}$ which can be found by solving $U_{1c}^{(1)} = U_{1c}^{(0)}$ for c_1 will be equal to or less than the threshold $\bar{c}_1$ as defined by (A.8). (Note that although $U_{1c}^{(0)}$ can be lower than the respective measure for costless prototyping, it holds only when the manufacturer chooses not to develop the second prototype irrespective of the first prototype outcome, and thus it does not affect the analysis.)

From (A.20), it follows that $(0,0)$ policy leads to the same thresholds as for costless prototyping if $\alpha\mathbb{E}_{c_1\le\bar{c}_1}\Pr\{w_2-c_2\ge w_1-c_1\}(R_2-w_2)-M\ge R_1-w_1$ holds true. Plugging in the values, we obtain $M\le\alpha\beta R_H-R_L$.

Solving the same for $(0,1)$ policy, we obtain $M\le\alpha(R_H-1)-R_L$. A sufficient condition for both inequalities to hold simultaneously is

$$M\le\begin{cases}\alpha(R_H-1)-R_L, & \text{if } R_H<\underline{R}^F;\\ \alpha\beta R_H-R_L, & \text{if } R_H\ge\underline{R}^F.\end{cases}\tag{A.22}$$

F scheme. The second-period target cost following a rejection will take the form

$$w_2^{(0)}=\begin{cases}0, & \text{if } \beta R_2>R_2-1 \text{ and } \alpha\beta R_2-M\ge 0;\\ 1, & \text{if } \beta R_2\le R_2-1 \text{ and } \alpha(R_2-1)-M\ge 0;\\ n/a, & \text{otherwise,}\end{cases}\tag{A.23}$$

where n/a means that the manufacturer chooses to stop the development process and not to declare any target cost for the second period. The rest of the analysis is similar to the C scheme with necessary changes of w_2 to $w_2^{(1)}$. Then, the policy $w_1=1-\alpha$, $w_2^{(1)}=2-\alpha$, and $w_2^{(0)}=1$ is optimal if $M\le\alpha(R_H-1)$ from (A.23) and $\alpha\mathbb{E}_{c_1\le\bar{c}_1}\Pr\{w_2^{(1)}-c_2\ge w_1-c_1\}(R_2-w_2^{(1)})-M\ge R_1-w_1$ which reduces to $M\le\alpha(R_H-2+\alpha)-R_L+1-\alpha$. Note that both inequalities hold under the conditions for the C scheme.

If M is too high, i.e., (A.22) does not hold, the manufacturer may prefer to develop only one prototype prototype, and clearly the optimal testing sequence can be reversed so that the manufacturer tests R_H first and possibly stops after that. It is intuitive that the threshold for testing costs increases in the performance difference and design success probability (α), since the former makes the F scheme with increasing performance sequencing more attractive and the latter augments the expected value of the second design making it more attractive for development.

A.7 Manufacturer's Objective Functions

A.7.1 C Scheme

In (2.4) the expectation is over the joint distribution of c_t and r_t. The realized c_t and r_t determine the thresholds $\bar{c}_t$. Expression (2.4) sums over each $i \in S$, assuming i is the manufacturer's final choice. The term $(r_i - w_i)^+ \equiv \max\{r_i - w_i, 0\}$ is his payoff from choosing i. For i to be finally chosen, it must be released by the supplier; the term $A(\bar{c}_i)$ is the probability. It must also give the manufacturer the highest payoff among all released prototypes; the probability, conditional on the set of other released prototypes s, equals the probability that all prototypes in $S \backslash \{i\} \backslash s$ are not released (i.e., $\prod_{j \in S \backslash \{i\} \backslash s} \overline{A}(\bar{c}_j)$) times the probability that all prototypes in s are released and yield no greater payoff (i.e., $\prod_{j \in s} A(\bar{c}_j) \Pr(r_i - w_i \geq r_j - w_j)$).

A.7.2 F scheme

We explain equation (2.5). The manufacturer chooses w_t to maximize his expected payoff. In (2.5), the expectation is over the distribution B_t and the random variable r_t. As previously explained, the threshold $\bar{c}_t$ depends on the unknown c_k; let $\bar{c}_t(c_k)$ denote the threshold given c_k. With probability $\overline{A}(\bar{c}_t)$, the supplier does not release the prototype, and hence $\pi_{t+1} = \pi_t$; $B_{t+1}^{(0)}$ denotes the manufacturer's updated belief in this case. With probability $A(\bar{c}_t)$, the supplier releases the prototype, and hence $\pi_{t+1} = \max\{r_t - w_t, \pi_t\}$; in this case, $B_{t+1}^{(1)}$ denotes the updated belief if the status-quo does not change (when $r_t - w_t < \pi_t$), and $B_{t+1}^{(2)}$ denotes the updated belief if the status-quo choice becomes design t (when $r_t - w_t \geq \pi_t$).

The manufacturer updates B_t to $B_{t+1}^{(0)}$, $B_{t+1}^{(1)}$, or $B_{t+1}^{(2)}$ per Bayes' rule. In particular, if the supplier does not release prototype t, the manufacturer knows that $c_t > \overline{c}_t$; therefore,

$$B_{t+1}^{(0)}(c) = \Pr[c_k < c | c_t > \overline{c}_t(c_k)] = \frac{\Pr[c_k < c \ \& \ c_t > \overline{c}_t(c_k)]}{\Pr[c_t > \overline{c}_t(c_k)]} = \frac{\int_{-\infty}^{c} \overline{A}(\overline{c}_t(c_k)) dB_t(c_k)}{\int_{-\infty}^{\infty} \overline{A}(\overline{c}_t(c_k)) dB_t(c_k)}. \tag{A.24}$$

However, if the supplier releases the prototype and the status-quo choice does not change, $B_t^{(1)}$ is the posterior distribution of c_k given that $c_t \leq \overline{c}_t(c_k)$, and therefore

$$B_{t+1}^{(1)}(c) = \Pr[c_k < c | c_t \leq \overline{c}_t(c_k)] = \frac{\Pr[c_k < c \ \& \ c_t \leq \overline{c}_t(c_k)]}{\Pr[c_t \leq \overline{c}_t(c_k)]} = \frac{\int_{-\infty}^{c} A(\overline{c}_t(c_k)) dB_t(c_k)}{\int_{-\infty}^{\infty} A(\overline{c}_t(c_k)) dB_t(c_k)}. \tag{A.25}$$

By contrast, $B_t^{(2)}$ is the distribution of c_t given that $c_t \leq \overline{c}_t(c_k)$, and therefore

$$B_{t+1}^{(2)}(c) = \Pr[c_t < c | c_t \leq \overline{c}_t(c_k)] = \frac{A(c)}{\int_{-\infty}^{\infty} A(\overline{c}_t(c_k)) dB_t(c_k)}. \tag{A.26}$$

Appendix B

Supplement for Chapter 3

B.1 Proof of Proposition 3.1

As the best response, supplier i exerts an ϵ higher effort than supplier j if her profit from winning the competition, i.e., the case $r_i(e_i) > r_j(e_j)$ in (3.1), exceeds her profit from the case $r_i(e_i) < r_j(e_j)$. Simplifying the profit difference from (3.1), we obtain $c(e_i) < c(r_i^{-1}(\bar{e}_j))$, or equivalently $e_i < r_i^{-1}(\bar{e}_j)$. Otherwise, supplier i exerts the minimum effort to satisfy the manufacturer's reservation performance, i.e., $e_i = r_i^{-1}(u)$, which proves (i).

Let the cumulative distribution functions $F_n(\cdot)$ and $F_c(\cdot)$ represent the mixed strategy used by player n and c, respectively. Then, the utility function from equation (3.1) is given as

$$v_i^T(e_i) = \Big(1 - F_j\Big(r_j^{-1}(r_i(e_i))\Big)\Big)S_i(1-S_j)u + F_j\Big(r_j^{-1}(r_i(e_i))\Big)S_i u - c(e_i)B_i \quad \text{(B.1)}$$

where $i \neq j$ and $i, j = n, c$.

At the equilibrium, each action e_i must yield the same payoff. Therefore,

$$S_i(1-S_j)u + F_j\Big(r_j^{-1}(r_i(e_i))\Big)S_iS_ju - c(e_i)B_i = const_i \tag{B.2}$$

And thus,

$$F_j\Big(r_j^{-1}(r_i(e_i))\Big) = \frac{const_i - S_i(1-S_j)u + c(e_i)B_i}{S_iS_ju} \tag{B.3}$$

We can find the constant from the terminal conditions which are different for supplier n and supplier c: $F_c\left(\bar{e}_c\right) = 1$ and $F_n\left(r_c^{-1}(r_n(\bar{e}_c))\right) = 1$, where $\bar{e}_c = 2^{-1}\left(\frac{S_nS_cu}{B_c} + c(\underline{e}_c)\right)$, where $c(\underline{e}_c) = r_c^{-1}(u)$.

Therefore,

$$F_n\left(x\right) = \begin{cases} 0, & \text{if } r_c^{-1}(r_n(x)) < \underline{e}_c; \\ \frac{B_c}{S_nS_cu}\left(c\left(r_c^{-1}(r_n(x))\right) - c\left(\underline{e}_c\right)\right), & \text{if } \underline{e}_c \leq r_c^{-1}(r_n(x)) < \bar{e}_c; \\ 1, & \text{if } r_c^{-1}(r_n(x)) \geq \bar{e}_c; \end{cases} \tag{B.4}$$

and

$$F_c\left(x\right) = \begin{cases} 0, & \text{if } x < \underline{e}_c; \\ 1 - \frac{B_n}{S_nS_cu}\left(c\left(r_n^{-1}(r_c(\bar{e}_c))\right) - c(r_n^{-1}(r_c(x)))\right), & \text{if } \underline{e}_c \leq x < \bar{e}_c; \, , \\ 1, & \text{if } x \geq \bar{e}_c; \end{cases} \tag{B.5}$$

which proves (ii).

B.2 Proof of Proposition 3.2

Let

$$\overline{\beta} = \arg_{\beta}\left\{\frac{\partial F_n(x)}{\partial t_c} = 0\right\} = \frac{-(1-\alpha)^{t_c}\ln(1-\alpha)}{1-(1-\alpha)^{t_c}+(t_c-1)(1-\alpha)^{t_c}\ln(1-\alpha)},$$

where $x \in \left[r_n^{-1}(r_c(\underline{e}_c)), r_n^{-1}(r_c(\bar{e}_c))\right)$.

Then $\forall\ \beta > \overline{\beta}, \forall\ x \in \left[r_n^{-1}(r_c(\underline{e}_c)), r_n^{-1}(r_c(\bar{e}_c))\right) : \frac{\partial F_n(x)}{\partial t_c} > 0$, which means that the probability of effort being less than any given x is increasing, and $\forall\ \beta < \overline{\beta}, \forall\ x \in \left[r_n^{-1}(r_c(\underline{e}_c)), r_n^{-1}(r_c(\bar{e}_c))\right) : \frac{\partial F_n(x)}{\partial t_c} < 0$, which means that the probability of effort being higher than any given x is increasing. Consider the border sensitivity to t_c. Note that $\frac{\partial r_n^{-1}(r_c(\underline{e}_c))}{\partial t_c} = 0$ and $\frac{\partial r_n^{-1}(r_c(\bar{e}_c))}{\partial t_c} < 0$ if $\beta > \overline{\beta}$ and $\frac{\partial r_n^{-1}(r_c(\bar{e}_c))}{\partial t_c} > 0$ if $\beta < \overline{\beta}$, which completes the proof.

B.3 Proof of Proposition 3.3

If $r_j(e_j) \leq r_i(\overline{e}_i^*)$, supplier i chooses the optimal effort level $\overline{e}_i^*$ which she exerts being the first-choice supplier of the manufacturer. However, if $r_j(e_j) > r_i(\overline{e}_i^*)$, supplier i can either choose the optimal effort level for the second-best choice of the manufacturer $\underline{e}_i^*$ or exert ϵ higher efforts than supplier j and become the first choice. Supplier i optimally chooses the former if $w_i\Big(r_i^{-1}(r_j(e_j)+\epsilon)\Big) < l_i(\underline{e}_i^*)$ and the latter otherwise, which proves (i).

Equating the best-response functions of the suppliers, we can see that the pure-strategies equilibria are $(\underline{e}_n^*, \overline{e}_c^*)$ and $(\overline{e}_n^*, \underline{e}_c^*)$, which proves (ii). And for the mixed-strategy equilibria, we solve the problem identical to the one in Proposition 3.1, and obtain (3.9), which proves (iii).

B.4 Proof of Proposition 3.4

To find the mixed-strategy Nash equilibria, we solve a system of equations ensuring the constant payoff of each supplier irrespective of the chosen action:

$$\begin{cases} \mu v^c_{LL} + (1-\mu)v^c_{HL} = \mu v^c_{LH} + (1-\mu)v^c_{HH} \\ \rho v^n_{LL} + (1-\rho)v^n_{LH} = \rho v^n_{HL} + (1-\rho)v^n_{HH} \end{cases} \tag{B.6}$$

where μ is the probability that supplier n exerts low effort, ρ is the probability that supplier c exerts low effort, v^i_{xz} is the supplier i payoff when supplier n exerts effort of x and supplier c exerts effort of z, where $i = n, c$ and $x, z = \{L, H\}$. Solving (B.6) for μ and ρ, we obtain $\rho = \frac{S_n y_n(e_H) - S_n(1-S_c)y_n(e_L) - \Delta_c B_n}{S_n S_c y_n(e_L)}$ and $\mu = \frac{\Delta_c B_c - S_c(1-S_n)(y_c(e_H) - y_c(e_L))}{S_n S_c y_c(e_L)}$, where $\Delta_c = c(e_H) - c(e_L)$. The pure-strategy Nash equilibria are derived directly from Table 3.1, which completes the proof.

B.5 Proof of Proposition 3.5

Isolating $\pi^T(2,1) - \pi^T(1,2)$ for β we obtain (3.11). Note that $\pi^T(2,1) - \pi^T(1,2)$ is monotone and increasing in β which completes the proof.

Appendix C

Supplement for Chapter 4

C.1 Proof of Proposition 4.1

Informed supplier releases the component if her expected profit is non-negative, i.e., if $\theta r_1 - (1-\theta)(l+r_0) \geq 0$. Solving for θ, we obtain $\theta \geq \frac{l+r_0}{r_1+l+r_0}$. Following the same logic, the supplier quits the development if $\theta < \frac{l+r_0}{r_1+l+r_0}$. Denoting $z = \frac{l+r_0}{r_1+l+r_0}$, we obtain

$$q_1^* = \begin{cases} 1 & \text{if } \theta \geq z \\ 0 & \text{if } \theta < z \end{cases}, \tag{C.1}$$

For the uninformed supplier, the corresponding condition for release is $\mathrm{E}_\theta\{\theta r_1 - (1-\theta)(l+r_0)\} \geq 0$, and hence the result is direct:

$$q_0^* = \begin{cases} 1 & \text{if } \mathrm{E}_\theta\{\theta r_1 - (1-\theta)(l+r_0)\} \geq 0 \\ 0 & \text{if } \mathrm{E}_\theta\{\theta r_1 - (1-\theta)(l+r_0)\} < 0 \end{cases}. \tag{C.2}$$

C.2 Proof of Proposition 4.2

If $\mathrm{E}_\theta\{\theta(R-S)-(1-\theta)L\} \geq 0$, equation (4.5) takes the form

$$\Big(1-F(z)\Big)\mathrm{E}_{\theta\geq z}\{\theta(R-S)-(1-\theta)L\}-c \geq \Big(\mathrm{E}_\theta\{\theta(R-S)-(1-\theta)L\}\Big).$$

Taking the (conditional) expected values and isolating for c, we obtain $c \leq \int_0^z \Big((1-\theta)L-\theta(R-S)\Big)f(\theta)\mathrm{d}\theta$.

If $\mathrm{E}_\theta\{\theta(R-S)-(1-\theta)L\} < 0$, equation (4.5) takes the form

$$\Big(1-F(z)\Big)\mathrm{E}_{\theta\geq z}\{\theta(R-S)-(1-\theta)L\}-c \geq 0.$$

Taking the conditional expected value and isolating for c, we obtain $c \leq \int_z^1 \Big(\theta(R-S)-(1-\theta)L\Big)f(\theta)\mathrm{d}\theta$.

C.3 Proof of Proposition 4.3

First, we find such $\underline{T}$ that the supplier's payoff from blind recommendation equals 0. We obtain $\underline{T} = \arg_T\{\mathrm{E}_\theta\{\theta(R-S-T)-(1-\theta)l\}=0\} = R-S-l\left(\frac{1}{\mathrm{E}_\theta\theta}-1\right)$.

Now assume that (4.9) does not hold at $T=\underline{T}$ meaning that the supplier chooses not to perform tests at $T=\underline{T}$. Then, $\forall T>\underline{T}: \mathrm{E}_\theta\{\theta(R-S-T)-(1-\theta)l\}<0$ which means that the supplier quits the development process. On the other hand, $\forall T<\underline{T}$, (4.9) does not hold while $\mathrm{E}_\theta\{\theta(R-S-T)-(1-\theta)l\}>0$ which means a stricter lower manufacturer's payoff than under $T=\underline{T}$. Therefore, $T^*=\underline{T}$, which proves (ii).

Now assume that (4.9) holds at $T = \underline{T}$. Similarly to the previous case, $\forall T < \underline{T}$, the supplier's behavior is unchanged while the manufacturer's payoff is strictly lower which makes these values of T suboptimal. Now recall that $\forall T > \underline{T}$: $\mathrm{E}_\theta\{\theta(R-S-T)-(1-\theta)l\} < 0$ and that $\int_{\hat{z}}^1 \Big(\theta(R-S)-(1-\theta)l-\theta T\Big) f(\theta)\mathrm{d}\theta$ is non-increasing in T, which means that there exists the maximum value of T at which the supplier chooses to perform tests rather than quitting the development. This value is $\overline{T} = \arg_T\{\Big(1-F(\hat{z})\Big)\mathrm{E}_{\theta\geq\hat{z}}\{\theta(R-S-T)-(1-\theta)l\} = c\} = \arg_T\{\int_{\hat{z}}^1 \Big(\theta(R-S)-(1-\theta)l-\theta T\Big) f(\theta)\mathrm{d}\theta = c\}$. Therefore, the optimal $T^* \in [\underline{T}, \overline{T}]$. Hence, $T^* = \arg\max_{T\in[\underline{T},\overline{T}]}\{(1-F(\hat{z})\mathrm{E}_{\theta\geq\hat{z}}\Big(\theta T-(1-\theta)L\} = \arg\max_{T\in[\underline{T},\overline{T}]}\{\int_{\hat{z}}^1 \Big(\theta T - (1-\theta)L\Big) f(\theta)\mathrm{d}\theta\}$, which proves (i).

C.4 Proof of Proposition 4.4

Recall that if (4.11) holds for some value of T, then it will hold for all $T' \geq T$, and for $T = 0$, (4.11) is equivalent to (4.5). It means that if (4.5) holds at $T = 0$, then (4.11) holds for all $T' \geq 0$. Therefore, the manufacturer can set the highest possible T satisfying the supplier participation constraint, which is $\Big(1-F(\tilde{z})\Big)\mathrm{E}_{\theta\geq\tilde{z}}\{\theta(R-S)-(1-\theta)L-T\} - c \geq 0$, which gives us (4.15), i.e., $T^* = \widetilde{T}$ and proves (i).

Now assume that (4.5) does not hold, which is equivalent to the fact that (4.11) does not hold at $T = 0$. Note that π_0 is increasing in T faster than π_1, or, more formally, $\frac{\partial \pi_0}{\partial T} \geq \frac{\partial \pi_1}{\partial T}$. Therefore, if $\pi_1(\widetilde{T}) \geq \pi_0(\widetilde{T})$ and the supplier chooses to test at $T = \widetilde{T}$, i.e., (4.11) holds at $T = \widetilde{T}$, then $T^* = \widetilde{T}$, which proves (ii), part 1.

If the supplier chooses not to test at the highest value of T, i.e., (4.11) does not hold at $T = \widetilde{T}$ (as well as at $T = 0$), it means that the manufacturer cannot induce the supplier to perform tests regardless of T, and the optimal solution is to set the highest possible T so that the supplier is indifferent between blind recommendation and quitting the development, which gives us $T^* = \arg_T \left\{ \Big(\mathrm{E}_\theta\{\theta(R-S) - (1 - \theta)L - T\} \Big)^+ = 0 \right\}$, which solves to $T^* = \mathrm{E}_\theta\{\theta(R-S) - (1-\theta)L\}$ proving (ii), part 2.

Finally, consider the case when the supplier chooses to test at $T = \widetilde{T}$, but the manufacturer would be better off if the supplier released the component blindly, i.e., $\pi_1(\widetilde{T}) < \pi_0(\widetilde{T})$. Given that $\frac{\partial \pi_0}{\partial T} \geq \frac{\partial \pi_1}{\partial T}$, it is optimal for the manufacturer to reduce T until the point when the supplier is indifferent between testing the component and releasing it blindly, which is achieved when (4.11) holds as strict equality, which proves (ii), part 3.

C.5 Proof of Proposition 4.5

The sufficient condition to achieve the first-best outcome is to ensure that the decision on testing the component is equivalent to the first-best scenario, i.e., to (4.5). It follows from the sample path argument: If any realization of random variables leads to the same decision under both contracts, it means that they lead to the same outcome, which is first-best in our case.

The supplier chooses to test the component if (following the logic of Proposition 4.1)

$$\Big(1 - F(\tilde{z})\Big)\mathrm{E}_{\theta \geq \tilde{z}}\{\theta(R-S) - (1-\theta)L - T\} - c - F(\tilde{z})T \\ \geq \Big(\mathrm{E}_\theta\{\theta(R-S) - (1-\theta)L - T\}, 0\Big)^+, \quad \text{(C.3)}$$

where $\tilde{z} = z = \frac{L}{R-S+L}$. Simplifying (C.3), we obtain

$$\Big(1-F(\tilde{z})\Big)\mathrm{E}_{\theta \geq \tilde{z}}\{\theta(R-S)-(1-\theta)L\}-c-T \geq \Big(\mathrm{E}_\theta\{\theta(R-S)-(1-\theta)L-T\}, 0\Big)^+. \quad \text{(C.4)}$$

We can see that if (C.4) holds at $T = 0$, i.e., (4.5) holds, it will hold for all $T \leq \big(1 - F(\tilde{z})\big)\mathrm{E}_{\theta \geq \tilde{z}}\{\theta(R-S)-(1-\theta)L\} - c$. Then, the optimal T for the manufacturer must capture the entire expected payoff and equal $T^* = \big(1 - F(z)\big)\mathrm{E}_{\theta \geq z}\{\theta(R - S) - (1-\theta)L\} - c$. If (C.4) does not hold at $T = 0$, i.e., (4.5) does not hold, the manufacturer cannot induce testing from the supplier, and sets the highest possible T ensuring supplier participation, which is $T^* = \mathrm{E}_\theta\{\theta(R-S)-(1-\theta)L\}$, thus proving (ii).

Plugging the optimal T^* into (C.4), we find it is equivalent to (4.5), which proves (i), and thus the first-best outcome is achieved.

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Titre : La conception collaborative de produit sous l'asymétrie d'information

Résumé : Les premières phases de conception de produit sont très importantes pour le développement de produits à succès, parce que jusqu'à 90 % des coûts des produits sont verrouillés durant les phases de concept et d'ingénierie. Lors de ces phases, les entreprises impliquent activement leurs fournisseurs à participer au développement du produit. Cependant, la littérature académique n'a pas accordé suffisamment d'attention au lien entre le stade de l'implication des fournisseurs précoce et le stade de production en série subséquente. Les objectifs de l'entreprise, qui développe le nouveau produit, et ses fournisseurs ne sont pas nécessairement alignés, ce qui peut entraîner de graves inefficacités. Par conséquent, l'objectif de cette thèse est de résoudre le conflit d'incitations à l'étape de la conception du produit, lorsque le fabricant d'un nouveau produit implique le fournisseur du composant clé. Cette thèse considère trois scénarios importants de la conception collaborative de produit : (1) les plusieurs conceptions alternatives du composant clé, (2) le développement de composants en parallèle par plusieurs fournisseurs, et (3) le test du composant clé par le fournisseur afin d'apprendre sa qualité. S'appuyant sur la méthodologie de la théorie des jeux non coopératifs, la thèse fournit des prescriptions pratiques sur la façon d'atténuer le décalage d'incitation dans chacun des trois scénarios.

Mots clés : conception de produit, collaboration, théorie des jeux

Title: Collaborative Product Development under Information Asymmetry

Abstract: Product design stage is utterly important for successful product development, as up to 90% of the product costs are locked in during the concept and design engineering phases. At these phases, manufacturers of new products actively involve their suppliers to participate in product development. However, academic literature has not given sufficient attention to the link between the early supplier involvement stage and the subsequent mass production stage. The goals of the product developing manufacturer and its suppliers are not necessarily aligned, which can result in serious inefficiencies. Therefore, the objective of this thesis is to resolve the conflict of incentives at the product design stage when a manufacturer of a new product involves a supplier of a key component. This thesis considers three important facets of collaborative product development: (1) multiple alternative designs of the key component, (2) parallel component development by several suppliers, and (3) testing of the key component by the supplier in order to learn its quality. Relying on the methodology of non-cooperative game theory, the thesis provides practical prescriptions on how to mitigate the incentive misalignment in each of the three cases.

Key words: product development, collaboration, game theory