Collaborative Prototyping of Alternative Designs Under a Target Costing Scheme

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Abstract

Prototyping allows firms to evaluate the technical feasibility of alternative product designs and to better estimate their costs. We study a collaborative prototyping scenario in which a manufacturer involves a supplier in the prototyping process by letting the supplier make detailed design choices for critical components and provide prototypes for testing. While the supplier can obtain private information about the costs, the manufacturer uses target costing to gain control over the design choice. We show that involving the supplier in the prototyping process has an important influence on the manufacturer's optimal decisions. The collaboration results in information asymmetry, which makes parallel prototyping less attractive and potentially reverses the optimal testing sequence under sequential prototyping: It may be optimal to test designs in increasing order of attractiveness to avoid that the supplier does not release technically and economically feasible prototypes for strategic reasons. We also find that the classical target costing approaches (cost- and market-based) need to be adjusted in the presence of alternative designs: Due to the strategic behavior of suppliers, it is not always optimal to provide identical target costs for designs with similar cost and performance estimates, nor to provide different target costs for dissimilar designs. Furthermore, the timing is important: While committing upfront to carefully chosen target costs

reduces the supplier's strategic behavior, in some circumstances the manufacturer can take advantage of this behavior by remaining flexible and specifying the second prototype's target costs later.

Key words: Collaborative prototyping; parallel and sequential testing; supplier involvement; target costing.

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1 Introduction

It is well known that a large portion of a product's lifecycle costs is locked in early, during product development (Clark and Fujimoto, 1991, p. 3). Therefore, prototyping has become an important tool, not only to test the technical feasibility of alternative designs but also to obtain better cost estimates (Mislick and Nussbaum, 2015), facilitating the choice of the final design. Before testing alternative designs, a firm needs to answer several questions: Should the firm use sequential or parallel testing? If the firm chooses sequential testing, which design should it test first and when should it stop testing the remaining alternatives? Prior studies have previously addressed these key questions assuming firms' new product development is mostly an internal process (see literature review for details).

Given that firms increasingly involve their suppliers in product development and component testing, this paper considers the case where a manufacturer outsources the development of design alternatives (for the same component) to the *same* supplier—as occurred, for example, in the design of the floor beams for the Boeing 787: A subsidiary of Tata Motors developed prototypes for two alternative designs, one using titanium and the other using composite material (Kulkarni, 2011). To tap into the supplier's design capabilities, the manufacturer provides only performance specifications, and it is the supplier who makes the detailed design choices for the particular component (Stuart and McCutcheon, 2000; Ro et al., 2008). However, this results in significant information asymmetry: By virtue of making product and process design decisions during the prototype development, it is now the supplier who will ultimately determine the component costs, and the supplier has little incentive to reveal the cost information to the manufacturer (Ro et al., 2008; Lamming et al., 2005).[1] Our first research question is therefore whether and how such supplier involvement

[1] For example, Ro et al. (2008) find that even in collaborative arrangements, U.S. car manufacturers do not achieve

influences the optimal testing strategy, given the information asymmetry.

To achieve control over their component costs, manufacturers may employ component-level target costing, a technique that is often advocated for such situations because "component-level target costing helps discipline and focus suppliers' creativity in ways beneficial to the buyer" (Cooper and Slagmulder, 1999, p. 24). The manufacturer determines a target cost for a component before the development takes place, which then serves as a prominent reference point for the subsequent mass production price of that component (Monczka et al., 2008, p. 413). The literature proposes two fundamental approaches to determining target costs: A cost-based approach, where 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 customer value minus a desired profit margin (Kato, 1993; Ellram, 2000). However, to the best of our knowledge, the literature does not consider incentive implications when a supplier designs alternatives for the *same* component. This motivates our second research question, namely, when should manufacturers set target costs for design alternatives (at the outset, or flexibly, just before developing a particular design), and how?

Our study shows that the information asymmetry resulting from the supplier involvement in the prototyping phase indeed has an important influence on the optimal prototyping decisions: We show that in this situation, parallel prototyping becomes less attractive than sequential prototyping. Moreover, for sequential prototyping, our model reveals that supplier involvement (and the resulting incentive conflicts) may force manufacturers to reverse the optimal testing sequence: It might be optimal to test the less attractive design alternatives first. Regarding our research question about target costing, we show that the joint testing of multiple design alternatives changes the optimal target costing levels, making neither a cost-based nor a market-based approach generally optimal. Interestingly, we demonstrate that manufacturers do not necessarily benefit from the flexibility of being able to decide target costs for the second prototype after seeing the result of the first prototype. Overall, our study provides guidance to managers about fine-tuning the target costing approach in the case of alternative designs.

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the level of trust required for having suppliers openly share their cost information, as Japanese manufacturers require their suppliers to do.

2 Literature Review

This paper contributes to two streams of literature. First, it contributes to the product development literature by presenting new findings that complement existing results regarding (a) sequential versus parallel testing and (b) the optimal sequence in which prototypes should be tested. Second, it contributes to the target costing literature by providing a new perspective about setting target costs when multiple design alternatives are being tested. In what follows, we review each literature stream.

Our paper is closely related to the literature on the optimal search for the best alternative (technology, design, prototype, etc.) over a specific landscape of potential solution candidates. The cornerstone question in this literature, laid out by Weitzman (1979), is the choice between sequential and parallel development (or testing) of alternatives. A number of papers have advanced our fundamental understanding of these approaches. Thomke and Bell (2001) study the optimal testing strategies for sequential testing and derive rules that define the optimal number of tests and the optimal test fidelity. Dahan and Mendelson (2001) extend the extreme-value theory to parallel testing scenarios and discuss the effects of probability distribution parameters on the optimal number of tests and the testing budget. More recently, Massala and Tsetlin (2015) analyze parallel testing of multi-attribute alternatives when the attributes exhibit uncertain relative importance; they focus on the optimal number of alternatives to explore in parallel.

One benefit of sequential testing that has been studied in detail in the literature is the ability to learn from the different sequential tests (Loch et al., 2001; Erat and Kavadias, 2008; Oraiopoulos and Kavadias, 2014). While our paper also considers sequential and parallel testing, we focus on the case where design alternatives differ sufficiently from each other so that the testing results from one alternative are uninformative regarding the performance of the other alternative. This allows us to show that a collaborative setting can make sequential development a preferable option even in the absence of cost savings or learning effects. It also adapts the well-known result in Weitzman (1979) on the optimal testing sequence for a single firm (which finds it optimal to test alternatives in decreasing order of attractiveness) to the scenario where a manufacturer involves a supplier in the prototyping stage, who can exploit the information asymmetry. Terwiesch and Loch (2004) and Basu and Bhaskaran (2015) also consider collaborative prototyping, or customer co-design of a product. However, in their context of custom-designed products, the supplier (i.e., the seller) provides the prototypes and sets the prices, while we consider a product design context in which the manufacturer (i.e., the customer) leads the process by setting the designs' target costs.

Our paper is also related to the recent research on incentive issues in collaborative new product development (where the product is developed jointly by multiple entities). Bhaskaran and Krishnan (2009) focus on alliances and analyze the revenue-, investment-, and innovation-sharing mechanisms between participating firms. Iyer et al. (2005) study vertical collaboration with hidden supplier capabilities. Kim and Netessine (2013) explore vertical collaborative efforts (exerted by both parties) to reduce the product cost. In our research, we forgo an analysis of the levels of effort in order to concentrate on the dynamics arising from the development of multiple prototypes.

The second stream of literature, on target costing, is largely practitioner-oriented and builds on case studies (see Ansari et al. (2006) for a comprehensive literature review). Kato (1993) and Cooper and Slagmulder (1999) explain the key principles of target costing in the context of product development, and Tani (1995) and Davila and Wouters (2004) discuss its benefits and drawbacks. To the best of our knowledge, the work by Mihm (2010) is a notable exception to the empirical work; it uses a formal modeling approach to study incentive issues in the practice of target costing. Specifically, Mihm focuses on the incentives of product engineers, comparing target costing with other management practices.

The empirical literature on target costing identifies 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 customer value minus a desired profit margin. However, the literature does not consider the influence of having multiple alternative designs prototyped by the same supplier. We contribute to the literature by showing that in this context, the manufacturer can benefit by deviating from both the cost- and the market-based approaches.

3 Model

A manufacturer ("he", also referred to as M) involves a supplier ("she", also referred to as V, for vendor) in the development of a component for a new product. Let us assume that M has two alternative new designs, denoted as a and b, as well as an outside option (e.g., the conventional design). M must choose at most one design for mass production. In principle, he will choose a particular new design if it proves to be cost-efficient and ensures a sufficiently high performance compared to the other new design and the outside option.

To assess the performance of a particular component design, the manufacturer asks the future component supplier to develop a prototype of the component, and then he must test the prototype. M has two options: (1) to ask V to develop the design alternatives and produce the prototypes in parallel and then test them, or (2) to ask V to first develop and produce one prototype, choosing whether or not to develop the second prototype once the performance of the first prototype has been determined.

Similar to prior studies on prototype testing, e.g., Terwiesch and Loch (2004), we model the performance of design i as a scalar. In particular, we assume that, if tested, the performance of prototype (design) $i \in \{a, b\}$ has binary outcomes, and the performance is either r_i with probability α_i or 0 with probability $1 - \alpha_i$. The value 0 captures technical failure as well as the possibility that the prototype does not meet certain system requirements, while r_i models the expected value that design i creates for the manufacturer per unit of the component if the design is technically feasible and chosen for mass production. For the analytical part of this study, we consider r_i to be in the interval $(0, 1)$. We assume that r_a and r_b are common knowledge.[2]

Before the prototypes are designed, both M and V have only a rough estimate of design i's mass production cost, c_i. We assume that they have the same prior belief that the values c_a and c_b are independently and uniformly distributed from zero to one. Let $g(c_i)$ and $G(c_i)$ denote the probability density function and the cumulative distribution function of c_i. The assumption of a common prior is reasonable for the target costing approach, in which 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).

V's detailed design and development of either prototype i allows her to obtain a better estimate of design i's mass production cost; for simplicity, we assume that she observes the exact value of c_i. We assume that the exact value of c_i is the supplier's private information, because her estimation

[2]This assumption is not necessary for our main analysis in §§4–6, in which we only need to ensure that V can infer whether M would order her to prototype the second design should the first design prove to be feasible.

involves a significant amount of V's private knowledge, such as her ability to reduce the cost in the long run (based on her technology know-how and the slope of her learning curve), her ability to use existing tooling for the chosen detailed design, and her lower-tier suppliers' capacities and technical readiness.

M uses target costing to ensure that the chosen design will be cost-efficient; this is an effective way for M to gain control over his costs despite his inferior knowledge during the prototyping stage. In particular, before ordering prototype i, M sets a target cost, denoted as w_i, and commits to making no adjustment after the prototype is developed. Since the value w_i is linked to the future unit price in the supplier's mass production contract, the supplier has an incentive to declare design i cost-inefficient if her estimated cost c_i is too high, thereby eliminating the possibility of the supply chain ending up with the choice of a product design that is too costly. Formally, we assume that V's payoff is $w_i - c_i$ if design i is chosen for mass production.

M bears a fixed cost each time he asks V to develop and produce a prototype for a design alternative. For example, a manufacturer incurs the cost of sharing design specifications with a supplier, but the manufacturer also frequently covers (part of) the prototyping costs, including the material costs, tooling, and even engineering hours; this assumption is also made in Iyer et al. (2005). The authors' personal conversations with key component suppliers in the telecommunication industry confirm that manufacturers often cover prototyping costs even when none of the prototypes are selected for mass production. To keep the notation simple, we use $K \geq 0$ to denote the fixed cost allocation per unit of the component. We consider scenarios where K is not prohibitively high relative to prototype performance, the probability of passing the tests, and V's production costs. Specifically, we assume that if prototype i were the only prototype, M would find it optimal to develop it, or, more formally, $\exists w_i \geq 0 : \alpha_i G(w_i)(r_i - w_i) \geq K$, which is equivalent to $K \leq \frac{\alpha_i r_i^2}{2}$.

We will now describe the sequence of events, as well as the information available to each player in our model. At the outset, M chooses whether to test the designs in parallel or sequentially. If he chooses to develop the two prototypes in parallel, M sets the target costs w_a and w_b upfront. If he chooses sequential development, he first decides which design to test first. In the sequential case, we use numerical subscripts 1 and 2 to represent the designs tested first and second, respectively. We also consider two different scenarios regard the timing for his setting the target costs w_1 and w_2. In the main part of the paper, we consider the case where M sets w_1 and w_2 together before ordering the first prototype, and we refer to this as the commitment case. In section §7, we consider M to have more flexibility, so that he sets w_2 only when he orders development of the second prototype.

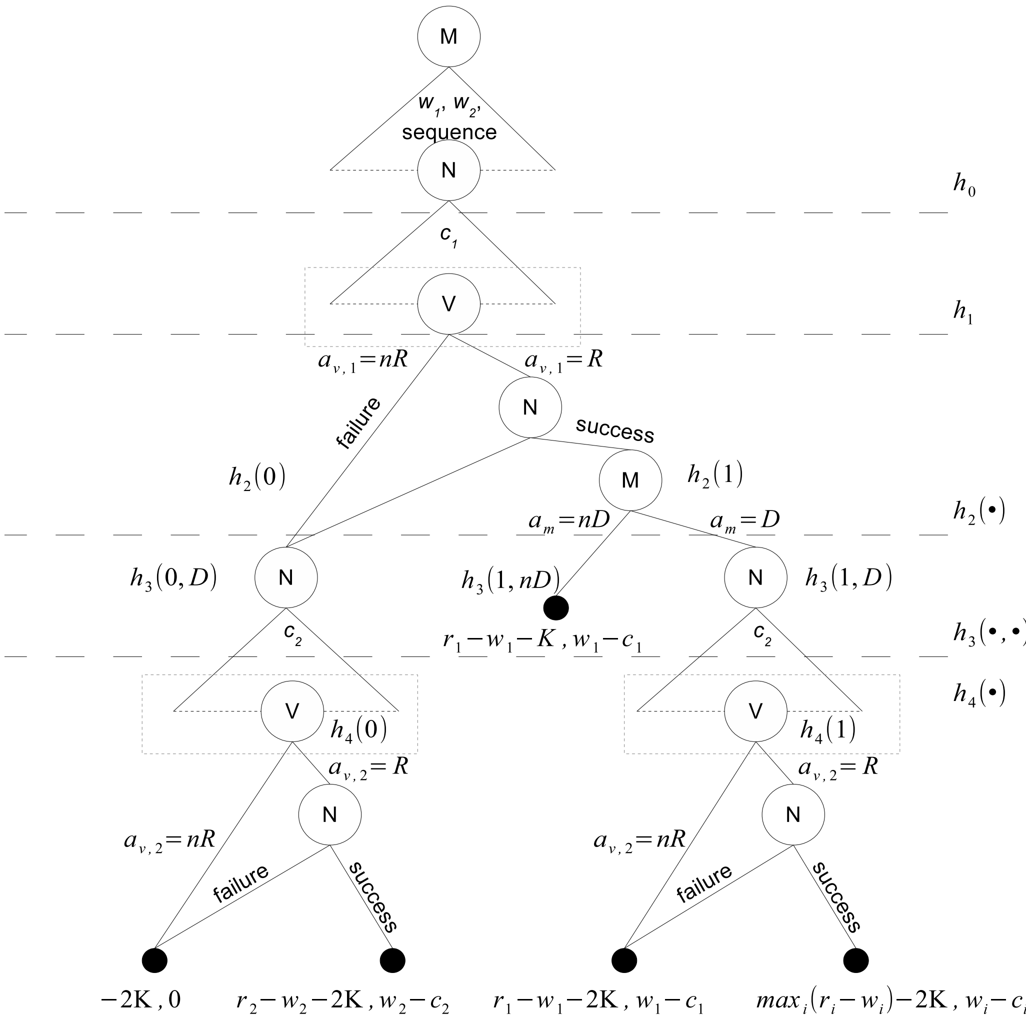


Figure 1: Simplified Game Tree

Figure 1 depicts the game tree for the commitment case, with M denoting a move by the manufacturer (M), N a move by nature, and V a move by the supplier (V).[3] First, M sets the target costs w_1 and w_2 and decides on the testing sequence. Next, V develops prototype 1 and observes its actual cost c_1. We denote the history at this point in the game as $h_1 \equiv \{w_1, w_2, r_1, r_2, c_1\}$, with c_1 representing V's private knowledge of c_1 and M knowing that V has observed this cost, and with r_1, r_2 representing M's sequence choice. Based on h_1, V chooses an action $a_{v,1} \in \{R, nR\}$, deciding whether to release (R) a particular prototype for testing or to declare it not to be cost-efficient and

[3]The parallel case follows a similar, but simpler timeline, since both prototypes are developed together and the supplier chooses all of her actions only once.

therefore not release it (nR). In other words, we assume that the manufacturer cannot force the supplier to release a prototype if the supplier is not able (or willing) to produce it at the specified target costs. Moreover, he will not renegotiate the target costs.[4]

If V releases prototype 1, the two firms jointly test prototype 1 and learn its performance value, which equals r_1 with probability α_1 or 0 with probability $(1-\alpha_1)$, where $\alpha_1 \in (0,1)$.[5] We call a prototype *feasible* if V declares it cost-efficient *and* it is technically and economically feasible for the manufacturer M, i.e., the performance value that is revealed during the prototype test exceeds its target cost w_1. We denote the history at this point as $h_2(1) \equiv \{w_1, w_2, r_1, r_2, c_1, 1\}$ (1 for one feasible prototype). If any one of the conditions does not hold, we call the prototype *infeasible* and we denote the history as $h_2(0) = \{w_1, w_2, r_1, r_2, c_1, 0\}$ (0 for zero feasible prototypes).

Note that we present a simplified game tree since two sets of information result in the same history $h_2(0)$: Either V chooses $a_{v,1} = nR$ or the performance of the released prototype turns out to be zero. In this case, the two information sets end up in the same subgame, since M does not obtain any information he needs to keep track of; neither the costs for nor the failure of the first prototype provides any information about the second prototype's costs or success probabilities (as the draws are i.i.d.), and since the first prototype is infeasible, its costs do not influence V's future action choice $a_{v,2}$ or either party's payoff.

At $h_2(1)$, M updates his belief about the cost of c_1 from $g(c_1)$ to $g(c_1|h_2(1))$. We assume M uses Bayes' rule to update his belief about V's private information (details are provided later).

M then chooses $a_m \in \{D, nD\}$, deciding whether to develop the second prototype (D) or not (nD). We denote the history at this point as $h_3(x,y) \equiv \{w_1, w_2, r_1, r_2, c_1, x, a_m\}$, with $x \in \{0,1\}$ representing the feasibility of the first prototype and $a_m \in \{D, nD\}$ capturing M's action choice. If $a_m = nD$, the game is over and both parties receive their payoffs, and if $a_m = D$, V privately observes c_2 and then chooses $a_{v,2} = \{R, nR\}$ based on the history at this point, which we denote as $h_4(x) \equiv \{w_1, w_2, r_1, r_2, c_1, x, D, c_2\}$, with $x \in \{0,1\}$ again capturing the feasibility of the first prototype.

In the following, we will denote the complete strategies of V and M as $\boldsymbol{s} \equiv (s_v, s_m)$. The action

[4] Renegotiation goes against the purpose of target costing, because it provides an incentive for the supplier to withhold the prototype strategically and ask for a higher target. This would make the use of target costing in future development cycles impossible.

[5] Such joint tests have become increasingly common because of high-tech solutions for collaborative prototype testing (Cisco, 2010; Wijtkamp, 2014).

space is $\{a_{v,1}, a_{v,2}\}$ and $\{r_1, w_1, w_2, a_m\}$ for V and M, respectively. In other words, V decides whether or not to release the first prototype and the second prototype, and M decides which prototype to test first, sets target costs for the first prototype and for the second prototype, and chooses whether or not to develop the second prototype.

Finally, either M chooses a feasible prototype i, and his payoff is $r_i - w_i$ (minus the prototyping costs) while the supplier's payoff is $w_i - c_i$, (for details, see Figure 1), or, if no feasible prototype is found, both parties receive their outside option, normalized to zero (minus costs). In the next sections, we derive the firms' expected payoff functions, denoting each firm j's ex-ante expected payoff given the strategies $\boldsymbol{s}$ as $\pi_j(\boldsymbol{s})$ and their expected payoffs "to go" given a history h_t as $\pi_j(\boldsymbol{s}|h_t)$, where $t = \{1, 2, 3, 4\}$ and $j = \{v, m\}$. We assume that both firms maximize their expected payoffs. If M is indifferent between the two prototype choices, we assume that M chooses prototype 2 in the sequential testing case (to avoid the possibility that V does not release the first prototype) and prototype a in the parallel testing case (without loss of generality). If V is indifferent between releasing (R) or not releasing (nR) a prototype, V will release the prototype.

The rest of the paper is organized as follows. In §4 we study the scenario where M chooses sequential prototyping, and in §5 we consider the parallel prototyping scenario. In §6 we compare the parallel and sequential prototyping. In §7 we further study the sequential prototyping scenario for the case where M uses an alternative target costing approach, delaying the announcement of w_2 (the target cost for the prototype that is tested second) until after the first prototype has been developed and tested. In §8 we summarize our findings.

4 Sequential Testing: Commitment Scheme

In this section, we solve the subproblem in which the manufacturer chooses sequential prototype testing and sets both w_1 and w_2 upfront. We refer to this setting as the Commitment scheme, or the C scheme for short.

4.1 V's Problems at $h_4(\cdot)$

Solving the problem backwards, we start with the supplier's choice of whether or not to release the second prototype, i.e., the choice of $a_{v,2} \in \{R, nR\}$. This decision depends on whether the first prototype was feasible ($h_4(1)$) or not ($h_4(0)$).

Based on the game tree, we derive V's expected profits (to go) at $h_4(\cdot)$ in equations (1) and (2):

$$\pi_v((s_v, s_m)|h_4(0)) = \begin{cases} 0, & \text{if } a_{v,2}(h_4(0)) = nR \\ \alpha_2(w_2 - c_2), & \text{if } a_{v,2}(h_4(0)) = R, \end{cases} \tag{1}$$

$$\pi_v((s_v, s_m)|h_4(1)) = \begin{cases} w_1 - c_1, & \text{if } a_{v,2}(h_4(1)) = nR \\ \alpha_2(w_2 - c_2) + (1 - \alpha_2)(w_1 - c_1), & \text{if } a_{v,2}(h_4(1)) = R. \end{cases} \tag{2}$$

Comparing V's profits in the two scenarios, we obtain V's optimal actions defined by the release thresholds, $\overline{c}_2^{(\cdot)}$, for prototype 2 in the two subgames:

$$a^*_{v,2}(h_4(0)) = \begin{cases} nR, & \text{if } c_2 > \overline{c}_2^{(0)} \\ R, & \text{if } c_2 \leq \overline{c}_2^{(0)}, \end{cases} \tag{3}$$

where $\overline{c}_2^{(0)} \equiv w_2$, and

$$a^*_{v,2}(h_4(1)) = \begin{cases} nR, & \text{if } c_2 > \overline{c}_2^{(1)} \\ R, & \text{if } c_2 \leq \overline{c}_2^{(1)}, \end{cases} \tag{4}$$

where $\overline{c}_2^{(1)} \equiv w_2 - (w_1 - c_1)$.

These results allow us to derive the optimal expected profits for V before c_2 has been observed, if the manufacturer orders the development of the second prototype, that is, given $h_3(\cdot, D)$:

$$\max_{a_{v,2}} \pi_v((s_v, s_m)|h_3(0, D)) \equiv \pi^*_v(\boldsymbol{s}|h_3(0, D)) = 0 + \alpha_2 \int_0^{\overline{c}_2^{(0)}} (w_2 - c_2) g(c_2)\, \mathrm{d}c_2 = \frac{\alpha_2 w_2^2}{2}, \tag{5}$$

$$\max_{a_{v,2}} \pi_v\left((s_v, s_m)|h_3(1, D)\right) \equiv \pi^*_v(\boldsymbol{s}|h_3(1, D)) = w_1 - c_1 + \alpha_2 \int_0^{\overline{c}_2^{(1)}} ((w_2 - c_2) - (w_1 - c_1)) g(c_2)\, \mathrm{d}c_2, \tag{6}$$

where $\int_0^{\overline{c}_2^{(1)}} ((w_2 - c_2) - (w_1 - c_1)) g(c_2)\, \mathrm{d}c_2 = \begin{cases} 0, & \text{if } \overline{c}_2^{(1)} < 0 \\ \frac{(w_2 - w_1 + c_1)^2}{2}, & \text{if } 0 \leq \overline{c}_2^{(1)} \leq 1 \\ w_2 - \frac{1}{2} - w_1 + c_1, & \text{if } \overline{c}_2^{(1)} > 1. \end{cases}$

Equations (5) and (6) are structurally similar: They add together the payoff from the first prototype, which is 0 for $h_3(0, D)$ and $w_1 - c_1$ for $h_3(1, D)$, and the expected added value of the second prototype.

Trivially, $\pi^*_v(\boldsymbol{s}|h_3(1, nD)) = r_1 - w_1$, as the development terminates in this case.

4.2 M's Problems at $h_2(\cdot)$

Next we turn to the manufacturer's action choice $a_m \in \{D, nD\}$, i.e., M's decision regarding whether to develop the second prototype.

If the first prototype is not feasible, i.e., the history is $h_2(0)$, M always develops the second prototype, as $\exists w_2 \geq 0 : \alpha_2 G(w_2)(r_2 - w_2) \geq K$ by assumption (or there would not be a reasonable second design alternative in the first place). V's expected optimal profits at $h_2(0)$ are hence identical to $h_3(0, D)$ above, and M's expected optimal profits at $h_2(0)$ are given by

$$\pi_m(\boldsymbol{s}|h_2(0)) = \alpha_2 G(w_2)(r_2 - w_2) - 2K, \tag{7}$$

where $G(w_2)$ captures the probability that V will optimally release the second prototype given the release threshold $\bar{c}_2^{(0)}$ derived above.

If the first prototype is feasible, i.e., the history is $h_2(1)$, M must decide whether to develop the second prototype, i.e., M must choose $a_m \in \{D, nD\}$. If he chooses $a_m = nD$, his expected payoffs are the payoffs from the first prototype, i.e., $r_1 - w_1 - K$. However, if he chooses $a_m = D$, his expected payoffs depend on how likely it is that V will release the second prototype, which depends, as we showed above, on V's private information c_1. Thus, M needs to update his belief about c_1 conditional on $h_2(1)$.

Note that for the updating, M must know V's strategy for the release of prototype 1. We follow the standard equilibrium analysis procedure and assume M believes that V chooses a particular strategy, which we will then show is indeed optimal for V. Consider a threshold-type policy, where V releases prototype 1 if and only if $c_1 \leq \bar{c}_1$, and assume that M's belief about this threshold is given by

$$\tilde{c}_1 = \begin{cases} w_1 - \pi_v^*(\boldsymbol{s}|h_2(0)), & \text{if } a_m^* = nD \\ w_1, & \text{if } a_m^* = D. \end{cases} \tag{8}$$

Using this assumption, M can update his belief and obtain the posterior probability distribution of c_1 as follows (the complete derivation is shown in Online Companion A.1):

$$g(c_1|h_2(1)) = \frac{g(h_2(1)|c_1)g(c_1)}{g(h_2(1))} = \begin{cases} \frac{1}{w_1}, & \text{if } 0 \leq c_1 \leq w_1 \\ 0, & \text{if } c_1 < 0 \text{ or } c_1 > w_1. \end{cases} \tag{9}$$

We can now derive M's expected profit at $h_2(1)$, given that the first prototype has been released. If M decides not to develop the second prototype, he will simply receive the first prototype's profits;

if he decides to develop it, he receives the additional margin of the second prototype if V releases the prototype (with probability $\int_0^{\widetilde{c}_1} G(\overline{c}_2^{(1)})g(c_1|h_2(1))\,\mathrm{d}c_1$) and the test turns out to be successful (with probability α_2), i.e.:

$$\pi_m(\boldsymbol{s}|h_2(1)) = \begin{cases} r_1 - w_1 - K, & \text{if } a_m = nD \\ r_1 - w_1 + \alpha_2\left((r_2 - w_2) - (r_1 - w_1)\right)\int_0^{\widetilde{c}_1} G(\overline{c}_2^{(1)})g(c_1|h_2(1))\,\mathrm{d}c_1 - 2K, & \text{if } a_m = D, \end{cases} \tag{10}$$

where $\widetilde{c}_1 = w_1$ and

$$\int_0^{w_1} G(\overline{c}_2^{(1)})g(c_1|h_2(1))\,\mathrm{d}c_1 \;=\; \begin{cases} \frac{\int_0^{w_1}(w_2-w_1+c_1)\,\mathrm{d}c_1}{w_1} = w_2 - \frac{w_1}{2}, & \text{if } w_2 \geq w_1 \\ \frac{\int_{w_1-w_2}^{w_1}(w_2-w_1+c_1)\,\mathrm{d}c_1}{w_1} = w_2 - \frac{w_1}{2} + \frac{(w_1-w_2)^2}{2w_1}, & \text{if } w_2 < w_1. \end{cases} \tag{11}$$

Comparing M's expected profits in these two cases, we can state M's optimal action choice a_m^* in Lemma 1:

Lemma 1. *The manufacturer's optimal action choice regarding whether or not to develop the second prototype is*

$$a_m^* = \begin{cases} D, & \text{if } \alpha_2\left((r_2 - w_2) - (r_1 - w_1)\right)\int_0^{w_1} G(\overline{c}_2^{(1)})g(c_1|h_2(1))\,\mathrm{d}c_1 \geq K \\ nD, & \text{otherwise.} \end{cases} \tag{12}$$

All the proofs are provided in the Appendix.

The lemma reveals some interesting insights. First, K needs to be small enough for the manufacturer to find it optimal to develop the second prototype. More interestingly, the prototypes also need to be tested in increasing order of attractiveness (to M), or M will not develop the second prototype, even at zero cost of testing. The reason is that M will definitely choose the first prototype for mass production, and thus developing the second does not add any value or alter V's behavior in any way.

We cannot simplify V's expected profit function further, so we use the following function for V's optimal expected profits at $h_2(1)$:

$$\pi_v^*(\boldsymbol{s}|h_2(1)) \equiv \begin{cases} \pi_v^*(\boldsymbol{s}|h_3(1,D)), & \text{if } a_m = D \\ \pi_v^*(\boldsymbol{s}|h_3(1,nD)), & \text{if } a_m = nD. \end{cases} \tag{13}$$

4.3 V's Problem at h_1

We now solve V's profit maximization problem at h_1, i.e., after observing c_1. V chooses $a_{v,1}$ to maximize her expected profits:

$$\pi_v\left(\boldsymbol{s}|h_1\right) = \begin{cases} \pi_v^*(\boldsymbol{s}|h_2(0)), & \text{if } a_{v,1} = nR \\ \alpha_1 \pi_v^*(\boldsymbol{s}|h_2(1)) + (1-\alpha_1)\pi_v^*(\boldsymbol{s}|h_2(0)), & \text{if } a_{v,1} = R. \end{cases} \quad (14)$$

Therefore, the supplier's best response is $a_{v,1}^* = R$ if $\pi_v^*(\boldsymbol{s}|h_2(1)) \geq \pi_v^*(\boldsymbol{s}|h_2(0))$, and $a_{v,1}^* = nR$ otherwise. Setting these profits equal and eliminating infeasible cases, we can state V's release threshold for the first prototype in Proposition 1:

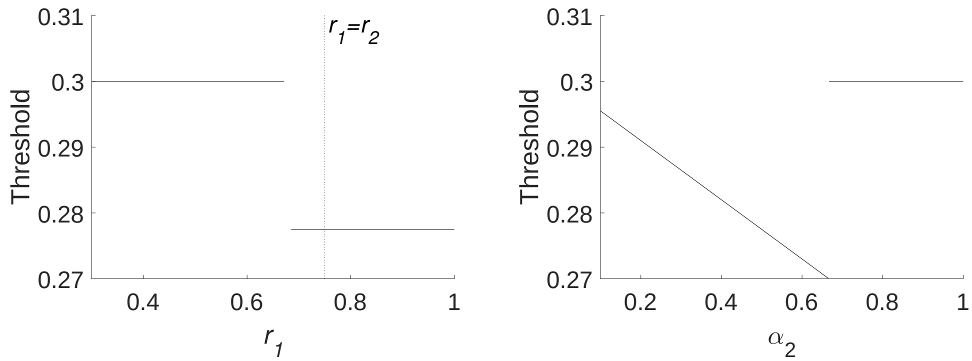
Proposition 1. *The supplier releases the first prototype if and only if $c_1 \leq \bar{c}_1$, where*

$$\bar{c}_1 = \begin{cases} w_1 - \pi_v^*(\boldsymbol{s}|h_2(0)), & \textit{if } \left((r_2 - w_2) - (r_1 - w_1)\right) \mathrm{Pr}_{success} < K \\ w_1, & \textit{if } \left((r_2 - w_2) - (r_1 - w_1)\right) \mathrm{Pr}_{success} \geq K \end{cases} \quad (15)$$

and $\mathrm{Pr}_{success} \equiv \alpha_2 \int_0^{w_1} G(\bar{c}_2^{(1)}) g(c_1|h_2(1))\, \mathrm{d}c_1$.

Note that this proposition confirms that the assumed manufacturer's belief about V's release threshold, $\widetilde{c}_1$, holds in equilibrium. The existence of the threshold $\bar{c}_1$ is intuitive. The supplier releases the prototype if and only if its cost estimation c_1 is sufficiently low. However, the main implication of Proposition 1 is that the release threshold can be *less than* the target cost w_1. If the manufacturer does not develop the second prototype in the case where the first prototype is feasible, the supplier may choose not to release the first prototype even if the prototype is profitable for both parties. Thus, while it might seem useful to test the more profitable prototype first (to avoid the testing costs K for a second prototype if the first one succeeds), testing the more profitable prototype first also destroys the supply chain value: Prototypes that could create positive value for both parties are withheld by the supplier for strategic reasons.

Figure 2(a) demonstrates the proposition with an example: The threshold is equal to the target cost if the prototype tested first has a relatively low profit margin (for low r_1). In that case, V is sure that M will test the second prototype regardless of the outcome of the first prototype test, and she can therefore safely release the first prototype as long as it does not generate a loss. However, if r_1 is sufficiently large, M will not test the second prototype if the first one succeeds. This makes the supplier cautious about releasing the first prototype, and thus the release threshold is below the target cost. It should be noted that this jump in the threshold level occurs not at $r_1 = r_2$ but rather for a lower value of r_1. This is the effect of the prototyping costs K. When the profit margin of the second prototype is marginally higher than that of the first, this is still not sufficient to convince M to develop the second prototype if the first one is feasible. A higher K would shift the discontinuity point even more to the left, while for $K = 0$ the discontinuity point would be at exactly $r_1 = r_2$.



(a) $\alpha_2 = 0.5$ (b) $r_1 = 0.7$

$\alpha_1 = 0.5$, $w_1 = w_2 = 0.3$, $r_2 = 0.75$, $K = 0.005$

Figure 2: $\bar{c}$ for different values of r_1 and α_2

Figure 2(b) demonstrates the impact of α_2, the probability of the second prototype passing the test, on this release threshold. If α_2 is sufficiently low, M will test the second prototype only if the first proves to be infeasible. In this case, an increase in α_2 leads to a higher expected profit for V from the second prototype, and thus V becomes increasingly reluctant to release the first prototype. This continues until α_2 becomes so high that M will always test the second prototype, thus stripping V of any strategic considerations.

4.4 M's Problem at h_0

We can now state the manufacturer's profit maximization problem at the outset of the game. The manufacturer will choose the order $\{r_1, r_2\}$ and the target costs $\{w_1, w_2\}$ by maximizing the following function:

$$\pi_m(\boldsymbol{s}) \equiv \alpha_1 G(\bar{c}_1)\pi_m(\boldsymbol{s}|h_2(1)) + (1-\alpha_1 G(\bar{c}_1))\pi_m(\boldsymbol{s}|h_2(0)) \tag{16}$$

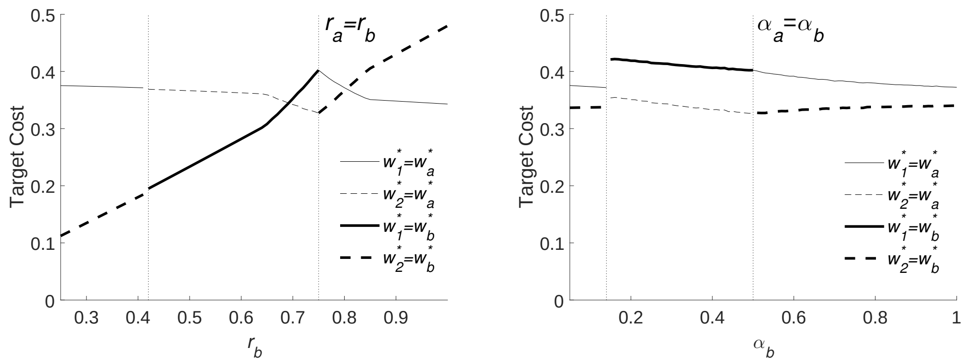
$$= \begin{cases} \alpha_1 G(w_1 - \frac{\alpha_1 w_2^2}{2})(r_1 - w_1 - K) \\ + \left(1 - \alpha_1 G(w_1 - \frac{\alpha_1 w_2^2}{2})\right)(\alpha_2 G(w_2)(r_2 - w_2) - 2K), & \text{if } a_m^* = nD \\ \alpha_1 G(w_1)\left(r_1 - w_1 + \alpha_2\left((r_2 - w_2) - (r_1 - w_1)\right)\int_0^{w_1} G(\bar{c}_2^{(1)})g(c_1|h_2(1))\,\mathrm{d}c_1\right) \\ +(1-\alpha_1 G(w_1))\alpha_2 G(w_2)(r_2 - w_2) - 2K, & \text{if } a_m^* = D, \end{cases} \tag{17}$$

where $\int_0^{w_1} G(\bar{c}_2^{(1)})g(c_1|h_2(1))\,\mathrm{d}c_1$ is given by (11).

We briefly describe this equation: If the manufacturer chooses the sequence and target costs such that $a_m^* = nD$, M will get the first prototype's profits if the supplier releases it ($G(\cdot)$) and the test succeeds (α_1), and he will instead get the second prototype's profits if the first one is not feasible ($1 - \alpha_1 G(\cdot)$) but the second is feasible ($\alpha_2 G(w_2)$)—the latter, however, at the cost of 2K. On the other hand, if the manufacturer chooses the sequence and target costs in such a way that $a_m^* = D$, M will once again get the first prototype's profits if V releases it ($G(w_1)$) and the test succeeds (α_1), but now also earns the additional margin on the second prototype if V releases it (the integral in line 3) and it succeeds (α_2). In addition, if the first prototype is infeasible (last row), M will still earn the profits on the second prototype if V releases it ($G(w_2)$) and it succeeds (α_2)—now, however, paying the prototyping costs for both prototypes.

While we cannot derive the order and the optimal target costs w_1 and w_2 in closed form, we can nevertheless derive some interesting properties.

First, we can show by example that neither market-based nor cost-based target costs are necessarily optimal when a manufacturer develops two alternative designs with the same supplier. Figure 3 provides an example of the optimal target costs and testing sequence for both symmetric and asymmetric design alternatives. Solid lines represent the target cost of the prototype tested first, and dashed lines represent the target cost of the prototype tested second. In addition, thick (solid or dashed) lines represent the target cost for prototype b. In Figure 3(a), the prototypes are symmetric when $r_a = r_b$. In Figure 3(b), the prototypes are symmetric when $\alpha_a = \alpha_b$. Both sets of examples demonstrate that symmetric design alternatives (symmetric in terms of probability of success and potential performance) do not necessarily require the same target costs for both prototypes, despite a priori identical costs, for which both market- and cost-based approaches suggest identical target costs for the two prototypes. The explanation for this is that asymmetric target costs mitigate the supplier's strategic non-release behavior. The figure also shows the impact of asymmetric designs on optimal target costs. We can see that the design with superior performance does not always require a higher target cost, and furthermore, that M should not necessarily test it first. (For example, prototype b is better than a in the range 0.75 to 0.8 but nevertheless has a lower target cost and is tested second.) For the case of identical performance, as per Figure 3(b), unless the risk of one prototype is extreme (in the utmost left region), M should test the riskier prototype first and set a higher target cost for it, as this is the only way that M can mitigate V's strategic non-release. Taken together, these results suggest that it is critical to take the supplier behavior into account when setting target costs.



(a) $\alpha_b = 0.5$ (b) $r_b = 0.75$

$\alpha_a = 0.5$, $r_a = 0.75$, $K = 0.005$; thick lines are target costs for prototype b

Figure 3: Optimal Testing Sequence and Target Costs for Different Values of α_b and r_b

Second, we can derive some results about the order in which prototypes should be tested. There are three distinct regions in Figure 3(a). If r_b is low (here, below 0.42), M finds it optimal to test the better prototype first and then stop if it succeeds. This can provoke V's strategic non-release but compensates for it by saving K if the first prototype succeeds. This region would disappear if $K = 0$. As prototype b gets better, w_b^* increases to improve its release probability should it be tested. Otherwise, if r_b is sufficiently high, M prefers to test the worse prototype first and then develop the second, no matter what. In this case, M completely eliminates V's strategic non-release, at the cost, however, of always testing both prototypes. This is the case in two regions: (1)

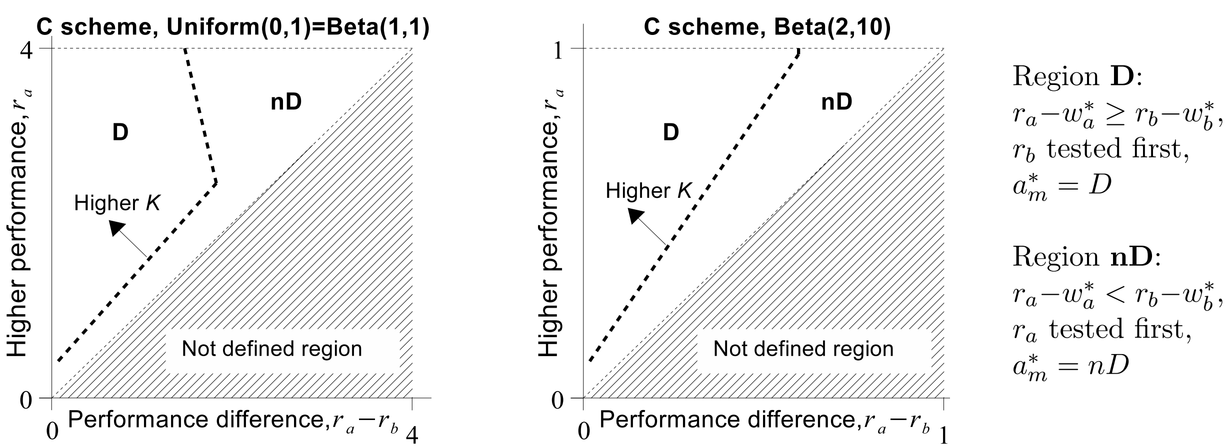
when r_b is the worse prototype ($r_b < r_a = 0.75$) and is tested first, and (2) when r_b is the better prototype ($r_b > r_a = 0.75$) and r_a is tested first. The intuition is similar for different values of α_b, as Figure 3(b) suggests.

We summarize the analytical results about the optimal testing order in Proposition 2:

Proposition 2. *If K is sufficiently small, it is always optimal to sequence the prototypes and choose target costs w_1^* and w_2^* such that they are tested in increasing order of attractiveness for M, i.e., such that $r_2 - w_2^* \geq r_1 - w_1^*$.*

In other words, our analysis suggests that if the per unit cost of prototyping, K, is not too large, the manufacturer should always test the design with the higher profit margin second, because this sequence mitigates the supplier's strategic non-release behavior for the first prototype by assuring the supplier that the manufacturer will always develop the second prototype and choose the last feasible design.

Figure 4 shows M's strategy in the C scheme for different payoff ranges (r_a). We present the charts for different cost distributions to extend the scope of our analytical results. We label the prototypes so that $r_a \geq r_b$. The vertical axis indicates the performance of the better prototype, r_a, and the horizontal axis the performance difference, $r_a - r_b$.



Beta(2,10) distribution is defined on $[0, 1]$, skewed to the left, unimodal with the mean equal to the mode.

Figure 4: C Scheme: M's optimal decisions at h_0 ($\alpha_a = \alpha_b = 0.5$ and $K = 0.005$)

If both prototypes have sufficiently high performance and the performance difference is not excessive (see region **D**), it is optimal for M to test the worse prototype first, that is, to choose

w_a and w_b so that the prototypes are tested in increasing order of attractiveness for M and to always test the second prototype, even if the first one is feasible. This strategy mitigates V's strategic non-release and is optimal as long as both prototypes feature high performance. However, if the performance of at least one of the prototypes is relatively low (see region **nD**), testing both prototypes is expensive. In that case, it is optimal for M to test the better prototype first and to develop the second one only in the case of failure. In this case, M will choose w_a and w_b such that the prototypes are tested in decreasing order of attractiveness for M. Note that this region disappears if K goes to zero, which is consistent with Proposition 2.[6]

The findings in the proposition and the figure complement the well-known result in the sequential testing literature (Weitzman, 1979) that suggests that a single decision-maker should always test designs in decreasing order of attractiveness (decreasing performance-to-cost ratio). The intuition behind starting the test with the most attractive design is that the tester can stop the search (testing) as early as possible to save search (testing) costs. Our analysis demonstrates that this intuition might not always hold when a third party is involved in the prototyping stage. The reason is that the supplier can take advantage of information asymmetry and not release a technically and economically feasible prototype, in the hope that the second prototype provides her with higher returns. Reversing the optimal testing sequence allows the manufacturer to avoid this strategic non-release. More specifically, in case of low testing costs, monetary or temporal, and a small enough performance difference, the manufacturer should reverse the testing sequence and test the more attractive, higher margin design second.

5 Parallel Prototyping

We now turn to the subproblem in which the manufacturer chooses parallel prototype testing. Here we have only two decision points: First, the manufacturer chooses the target costs w_a and w_b for prototypes a and b, respectively. Second, upon the completion of the prototypes, the supplier observes both costs, c_a and c_b, and then chooses whether to release (R_i) or not release (nR_i) each prototype i, i.e., the supplier chooses $a_{v,a} \in \{R_a, nR_a\}$ and $a_{v,b} \in \{R_b, nR_b\}$. Again we solve the problem backward, starting with the supplier.

[6]Note that the **nD** region becomes larger (non-linearity in the dashed line in Figure 4, left-hand side) if the performance of at least one prototype is significantly higher than the maximum component cost. This is not surprising. In this case, M can afford higher target costs, and these approach the maximum possible costs for V, reducing the probability of V's strategic non-release until eventually V always releases the first prototype.

Let $\overline{\overline{\pi}}_v(a_{v,a}, a_{v,b})$ denote V's expected payoff associated with her action choices. We label the prototypes as a and b in such a way that $r_a - w_a \geq r_b - w_b$.[7] Thus, V's expected payoff given her action choices is

$$\overline{\overline{\pi}}_v(a_{v,a}, a_{v,b}) = \begin{cases} \alpha_i(w_i - c_i), & \text{if } a_{v,i} = R_i \text{ and } a_{v,-i} = nR_{-i} \\ \alpha_a(w_a - c_a) + (1-\alpha_a)\alpha_b(w_b - c_b), & \text{if } a_{v,a} = R_a \text{ and } a_{v,b} = R_b \\ 0, & \text{otherwise.} \end{cases} \tag{18}$$

Comparing V's expected profits under the 4 scenarios, we state her release thresholds in the following proposition:

Proposition 3. *In the case of parallel prototyping, the supplier releases prototype a if and only if $c_a \leq w_a - \max\{0, \overline{\overline{\pi}}_v(nR_a, R_b)\}$, and she releases prototype b if and only if $c_b \leq w_b$.*

The release thresholds are structurally similar to those for sequential testing. The thresholds can be either equal to the target cost or lower by an amount equal to the supplier's expected profit from the other prototype. However, there is a profound difference: When testing in parallel, it is always the prototype with the higher profit margin (labeled as prototype a) that has a lower release threshold than the target cost. This is not the case for the sequential testing, as the manufacturer can always choose a testing sequence such that the prototype with the higher profit margin has a release threshold equal to the target cost.

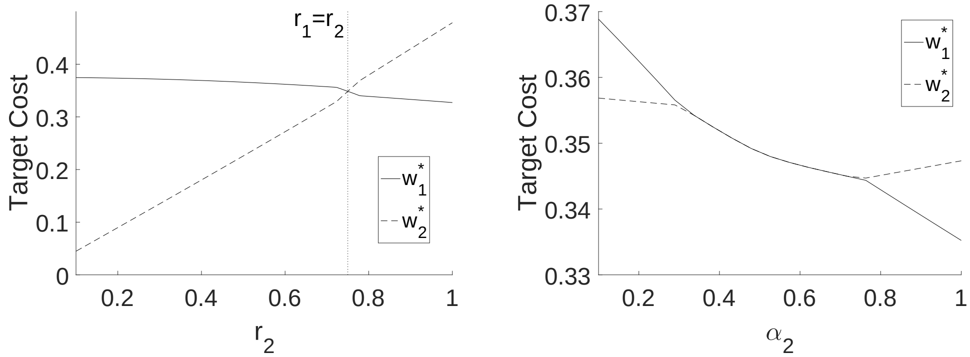
We can now derive the manufacturer's expected payoff:

$$\begin{aligned} \overline{\overline{\pi}}_m = &\int_0^{w_b} \Big(\alpha_a G(w_a - \overline{\overline{\pi}}_v(nR_a, R_b))(r_a - w_a) + \big(1 - \alpha_a G(w_a - \overline{\overline{\pi}}_v(nR_a, R_b))\big)\,\alpha_b(r_b - w_b)\Big) g(c_b)\,\mathrm{d}c_b \\ &+ \int_{w_b}^{1} \alpha_a G(w_a - 0)(r_a - w_a) g(c_b)\,\mathrm{d}c_b - 2K \\ &= w_b \left(\left[w_a - \alpha_b \frac{w_b}{2}\right]^+ \alpha_a(r_a - w_a) + \left(1 - \left[w_a - \alpha_b \frac{w_b}{2}\right]^+\right) \alpha_b(r_b - w_b)\right) \\ &\quad + (1 - w_b) w_a \alpha_a (r_a - w_a) - 2K. \end{aligned} \tag{19}$$

Again, we explain the expression: If $c_b \leq w_b$, V releases prototype a with probability $G(w_a - \overline{\overline{\pi}}_v(nR_a, R_b))$, and if it passes the test (with probability α_a), M will surely adopt it for mass production and receive the profit margin $r_a - w_a$. However, if prototype a is infeasible (with probability $1 - \alpha_a G(w_a - \overline{\overline{\pi}}_v(nR_a, R_b))$), the manufacturer will adopt prototype b if it passes the

[7] If $r_a - w_a = r_b - w_b$ and both prototypes are feasible, we let the manufacturer choose prototype a.

test (with probability α_b). If $c_b > w_b$, the difference is that V releases prototype a with probability $G(w_a - 0)$, and if it passes the test, M receives $r_a - w_a$. However, if prototype a is infeasible, no prototype will be adopted in this case. Finally, when testing prototypes in parallel, M always has to bear the prototyping costs for both prototypes, $2K$.



(a) $\alpha_2 = 0.5$ (b) $r_2 = 0.75$

$\alpha_1 = 0.5$, $r_1 = 0.75$, $K = 0.005$

Figure 5: Optimal Target Costs for Different Values of r_2 and α_2: Parallel Testing

As in the sequential case, there is no closed-form solution for the optimal target costs, but once again they can be determined for a specific set of parameters. Figure 5(a) demonstrates that the manufacturer, as one would expect, should generally set a higher (lower) target cost for a prototype with better (worse) performance.[8] If the prototypes have the same performance, as Figure 5(b) shows, the manufacturer should set equal target costs for the two prototypes for a large range of values of α_2, and not only when $\alpha_2 = \alpha_1$. The explanation is that an increase in one of the target costs leads to a lower release threshold for the other prototype. For this reason, if the prototypes are similar enough, the manufacturer does not find it optimal to differentiate the target costs. The effect is so strong that the manufacturer finds it optimal to reduce w_2^* as α_2 increases.

6 Comparison of parallel and sequential prototyping

We now turn to a comparison of parallel and sequential prototyping. Comparing the manufacturer's optimal payoff under the parallel prototyping ($\overline{\overline{\pi}}_m$ in equation 19) to that under the sequential prototyping (π in equation 16), we can show the following:

[8]In Figure 5, we use subscripts 1 and 2 merely for notational convenience because the labels 'a' and 'b' are determined after the values of target costs are set.

Proposition 4. *The optimal target costing policy under parallel prototyping is strictly dominated by the optimal policy under sequential prototyping, even for zero prototyping costs ($K = 0$).*

The result in Proposition 4 demonstrates an additional benefit of sequential prototyping, beyond saving prototyping costs and allowing the manufacturer to learn from one prototype to the next (two factors already explored in the literature; the latter is intentionally omitted in this paper): If a supplier is involved in the prototyping process, sequential prototyping lessens the strategic behavior of the supplier, and that alone can make sequential prototyping optimal, even for a zero cost of prototyping.[9]

Clearly, if there are important time-to-market benefits, which are ignored in our model, this can override the benefits of sequential prototyping. However, time-to-market benefits are only relevant if the development of this particular component is time critical. This might not be the case since this component's development might not even be on the critical path of the overall development project. In addition, if the time-to-market benefits are only small (which for a single decision-maker would make parallel prototyping optimal), in collaborative prototyping the incentive effects could potentially outweigh these benefits and make sequential prototyping optimal.

7 Flexible Target Costing in Sequential Testing

In this section, we revisit the sequential prototyping scenario and study the case in which the manufacturer uses the following flexible target costing scheme: He sets w_2 only after observing the outcome of the first prototype development. The interesting question is: When does the manufacturer benefit from such flexibility? Note that the choice between a pre-committed target cost and a flexible target costing scheme can only improve the sequential prototyping for the manufacturer. Hence, the sequential testing will continue to dominate the parallel testing, and the results of the comparison in Section 6 will remain intact.

We consider the same sequential game as in section 4, with one difference: At $h_2(\cdot)$, the manufacturer not only decides whether to develop the second prototype, but also chooses the target costs for the second prototype depending on the outcome of the first prototype. Thus, compared to the commitment scheme, we now have two different target costs for the second prototype: $w_{2f}^{(0)}$ for the target costs chosen at $h_2(0)$, i.e., when the first prototype is not feasible, and $w_{2f}^{(1)}$ at $h_2(1)$,

[9] In Online Companion B.1, we demonstrate that this result continues to hold for different cost distributions.

i.e., when the first prototype is feasible. Otherwise, the problem remains structurally the same and we keep the same notation, using the subscript f when it is useful to differentiate the notations under the flexible target costing scheme.

Once again solving the problem backward, we begin with V's action choice $a_{v,2} \in \{R, nR\}$ and obtain the same release thresholds at h_4 for the second prototype with one difference: They now depend on the target costs, which may be different for the two histories at h_4: $\bar{c}_{2f}^{(0)} \equiv w_{2f}^{(0)}$ at $h_4(0)$ and $\bar{c}_{2f}^{(1)} \equiv w_{2f}^{(1)} - (w_{1f} - c_1)$ at $h_4(1)$, where w_{1f} is the target cost of the prototype tested first.

7.1 Optimal $w_{2f}^{(\cdot)}$

V's and M's expected profit functions at $h_2(\cdot)$ do not change structurally, and hence the results (including those about a_m in Lemma 1) continue to hold. However, the profits now depend on different beliefs about V's release threshold for prototype 1 (see below) as well as two different target costs, depending on the feasibility of the first prototype. This allows us to solve for the optimal target costs for the second prototype in closed form.

For $h_2(1)$, as in the commitment scheme, M needs to again form a belief $\widetilde{c}_{1f}$ about V's release threshold and to update his prior regarding c_1. Again using Bayesian updating, his posterior belief about c_1 at $h_2(1)$ is given by:

$$g_f(c_1|h_2(1)) \equiv g_f(c_1|h_2(1), [0,1]) = \begin{cases} \frac{1}{\widetilde{c}_{1f}}, & \text{if } 0 \leq c_1 \leq \widetilde{c}_{1f} \\ 0, & \text{if } c_1 < 0 \text{ or } c_1 > \widetilde{c}_{1f}. \end{cases} \tag{20}$$

Using this, we can now derive the optimal target costs for the second prototype (for complete derivations see Online Companion A.2):[10]

$$w_{2f}^{(0)*} = \frac{r_2}{2}, \tag{21}$$

$$w_{2f}^{(1)*} = \max\left\{0, \min\left\{w_{1f} + \frac{r_2 - r_1}{2} - \frac{\widetilde{c}_{1f}}{4}, w_{1f} + 1 - \widetilde{c}_{1f}\right\}\right\}. \tag{22}$$

We can see that $w_{2f}^{(1)*}$ depends on M's (rational) belief about V's release threshold. V will hence take this impact into consideration when choosing $a_{v,1} \in \{R, nR\}$.[11]

7.2 V's Decision at h_1

Proposition 5 describes the supplier's release threshold for the first prototype.

[10] In the proof of Proposition 5, we will show that $w_{2f}^{(1)*}$ simplifies to $w_{2f}^{(1)*} = \max\left\{0, w_{1f} + \frac{r_2 - r_1}{2} - \frac{\widetilde{c}_{1f}}{4}\right\}$.

[11] Note that this does not mean that M can signal a "wrong" belief about the release threshold, so M's belief does not influence V's choice. Similarly, V cannot credibly announce a "wrong" threshold to M and hence cannot manipulate $w_{2f}^{(1)}$. It only means that V knows and takes into account that M will have rational beliefs about her release threshold and that M will take those into account in his choice of $w_{2f}^{(1)}$.

Proposition 5. *The supplier releases the first prototype if and only if* $c_1 \leq \overline{c}_{1f}$*, where*

$$\overline{c}_{1f} = \begin{cases} w_{1f} - \pi^*_{vf}(\boldsymbol{s}_f|h_2(0)), & \text{if } \left((r_2 - w^{(1)*}_{2f}) - (r_1 - w_{1f})\right) \mathrm{Pr}_{success,f} < K \\ \overline{C}, & \text{if } \left((r_2 - w^{(1)*}_{2f}) - (r_1 - w_{1f})\right) \mathrm{Pr}_{success,f} \geq K \end{cases}, \tag{23}$$

with $\overline{C} = \frac{2}{9} \cdot \frac{8+3\alpha_2(r_2-r_1)+4\sqrt{4-3\alpha_2(r_2-r_1)-\frac{9}{2}\alpha_2\left(w_{1f}-\pi^*_{vf}(\boldsymbol{s}_f|h_2(0))\right)}}{\alpha_2}$

and $\mathrm{Pr}_{success,f} = \alpha_2 \int_0^{\overline{C}} G\left(c_2 \leq \overline{c}^{(1)}_{2f}\right) g_f(c_1|h_2(1))\,\mathrm{d}c_1$.

Corollary 1. *If* $\left((r_2 - w^{(1)*}_{2f}) - (r_1 - w_{1f})\right) \mathrm{Pr}_{success,f} \geq K$ *and* $w_{1f} > \frac{2}{3}r_1$*, then* $\overline{c}_{1f} > w_{1f}$*. Otherwise,* $\overline{c}_{1f} \leq w_{1f}$*.*

Corollary 1 reveals an important difference from sequential testing without flexibility: the prototype release threshold $\overline{c}_f$ can be *greater* than w_1, that is, V might find it optimal to act strategically and release a prototype that is unprofitable for her.[12] In particular, this is the case if the first-period target cost is sufficiently large, and the manufacturer will choose to develop the second prototype, even if the first prototype succeeds. By releasing the first, less profitable prototype, the supplier makes the manufacturer believe that the first prototype could be profitable for her and that she will be reluctant to release the second prototype. To overcome this reluctance, the manufacturer will choose higher target costs for the second prototype if the first one has been accepted, i.e., $w^{(1)*}_2 > w^{(0)*}_2$.

7.3 M's Problem at h_0

At h_0, the manufacturer again chooses the order of the prototypes and in this case the optimal target costs for the first prototype. His profit maximization problem is given by[13]

$$\begin{aligned} \pi_{mf}(\boldsymbol{s}_f|h_0) &= \alpha_1 G(\overline{c}_{1f})\pi_{mf}(\boldsymbol{s}_f|h_2(1)) + (1-\alpha_1 G(\overline{c}_{1f}))\pi_{mf}(\boldsymbol{s}_f|h_2(0)) \\ &= \begin{cases} \alpha_1 G(\overline{c}_{1f})(r_1 - w_{1f} - K) \\ + (1-\alpha_1 G(\overline{c}_{1f}))\left(\alpha_2 G(w^{(0)*}_{2f})(r_2 - w^{(0)*}_{2f}) - 2K\right), & \text{if } a^*_m = nD \\ \alpha_1 G(\overline{c}_{1f})\left(r_1 - w_{1f} + \left((r_2 - w^{(1)*}_{2f}) - (r_1 - w_{1f})\right)\mathrm{Pr}_{success,f}\right) \\ + (1-\alpha_1 G(\overline{c}_{1f}))\alpha_2 G(w^{(0)*}_{2f})(r_2 - w^{(0)*}_{2f}) - 2K, & \text{if } a^*_m = D. \end{cases} \end{aligned} \tag{24}$$

As in the commitment case, we cannot solve this in closed form. However, by solving the problem numerically, we can derive some interesting results.

[12] Or rather, one with low profits, below the outside option, which we normalized to zero.

[13] For explanations regarding this equation, we refer the reader to those provided for equation (16) in the commitment scheme, which is structurally very similar.

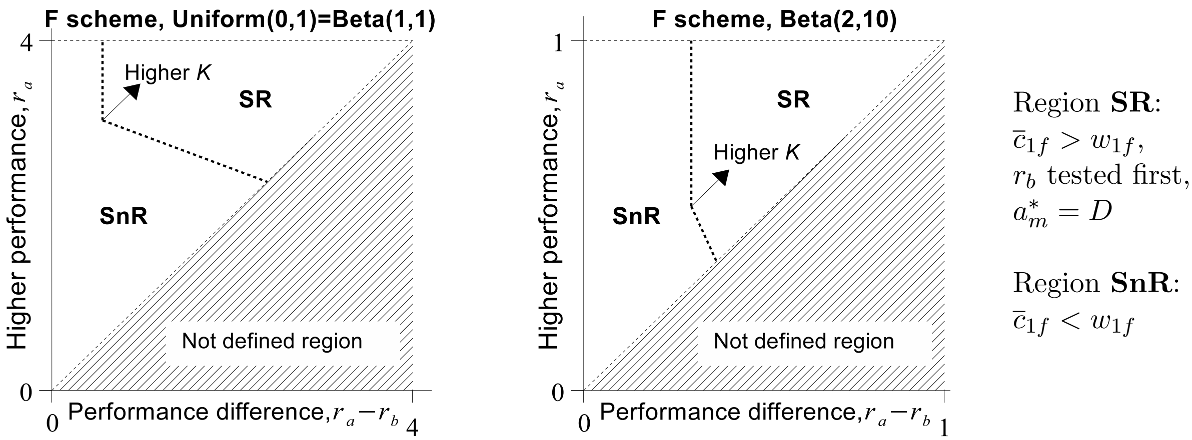


Figure 6: F Scheme: M's optimal decisions at h_0 ($\alpha_a = \alpha_b = 0.5$ and $K = 0.005$)

Figure 6 shows M's optimal decisions for two different cost distributions. It demonstrates that it is indeed sometimes optimal for M to take advantage of V's strategic release behavior, region **SR**, and to set w_1 and choose the prototyping sequence in such a way that V will release the first prototype even if the true cost exceeds the target cost, i.e., $c_1 > w_{1f}$. However, this is only possible if the prototype that is tested second has a sufficiently high performance (compared to the expected costs) and the performance difference is large enough. In this case, both M and V know that the second prototype is much more attractive to M. Releasing the first prototype (if it passes the tests), V credibly signals to M that she will be more reluctant to release the attractive second prototype as she may prefer to proceed with the first. This forces M to set an exceptionally high target cost for the second prototype. However, knowing these considerations upfront, M can set a sufficiently low w_1 and thus benefit from V's strategic release.

In region **SnR** (strategic non-release), M cannot credibly convince V that $w_{2f}^{(1)*}$ will be high enough. If the two prototypes have similar performance, M will stop if the first prototype is feasible, and hence there is no incentive for V to release strategically. If the performance difference is high but neither prototype has an exceptionally high performance, $w_{2f}^{(1)*}$ cannot be set high enough to incentivize V's strategic release.

7.4 Comparison of the Flexible Scheme to the Commitment Scheme

Since we do not have closed-form solutions, we designed extensive numerical studies to compare the manufacturer equilibrium expected profit under the flexible target costing scheme to the expected profits under the fixed target costs, as studied in section 4. Figure 7 represents the results of the expected profit comparison for the two target costing approaches under different cost distributions;

arrows represent the impact of K on this comparison.

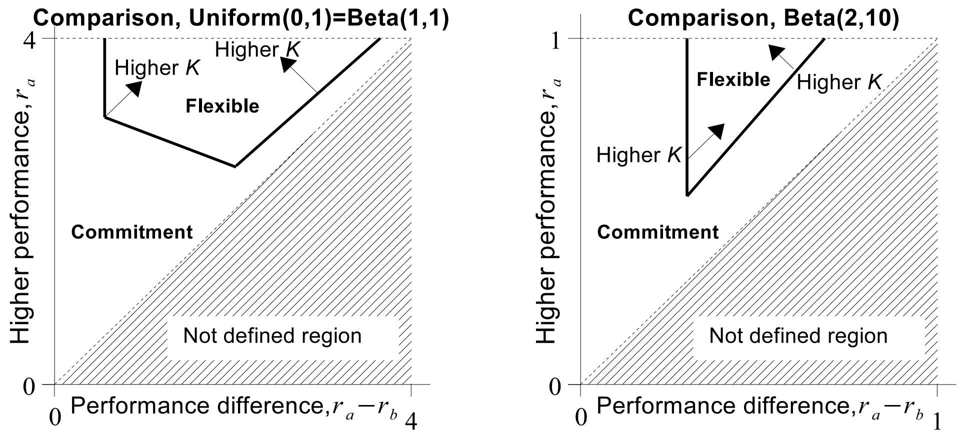


Figure 7: C versus F Scheme Comparison: $\alpha_a = \alpha_b = 0.5$ and $K = 0.005$

When and why should the manufacturer prefer flexibility to commitment? The short answer based on our numerics[14] is: only when V would strategically release the first prototype. However, it is not optimal for M to always take advantage of the strategic release: If the performance difference is too high, i.e., one prototype has a very low performance, the C scheme performs better. The reason is that M can save by stopping after developing the first prototype and thus avoid incurring K twice, while the optimal F scheme would imply testing both prototypes. With this reason in mind, we can now see why the optimal region of the F scheme shrinks as K increases. Under a high value of K, the benefit of favorable supplier behavior cannot outweigh the cost of developing the low performing prototype b, and thus the manufacturer is better off committing to target costs upfront and not testing the second prototype at all, if prototype a turns out to be feasible.

8 Conclusion

In this paper, we study a stylized model in which a manufacturer involves a supplier in the joint development and testing of prototypes for two alternative designs for a new product component. We show that the involvement of the supplier influences the manufacturer's optimal decisions: The supplier may not release prototypes that would be profitable for both parties or may release prototypes that are unprofitable for her. Therefore, when involving the supplier in product development, the manufacturer should not blindly copy conventional strategies used in single-firm development but should rather take the supplier's strategic behavior into account.

[14] We ran numerous additional scenarios, for different levels of α_i and K, and different cost distributions. While the exact cutoffs naturally differ, all look structurally similar. In Online Companion B.2, we provide the graphs for an additional example, where the more profitable prototype is also riskier, i.e., $\alpha_a < \alpha_b$.

Our study shows that the information asymmetry resulting from the supplier's involvement in prototype testing makes sequential prototyping generally more attractive. While the manufacturer can mitigate the supplier's strategic behavior if prototypes are tested sequentially, this is impossible to achieve if the testing is done in parallel. This has implications for manufacturers facing time-to-market pressure. In the presence of time-to-market pressure, a fully informed manufacturer (no information asymmetry) would test components concurrently if testing is not too expensive. However, supplier involvement breaks with this logic by introducing information asymmetry, thereby favoring sequential testing despite low testing cost unless the time-to-market pressure is excessive.

It is known that prototyping should be done in a sequence of decreasing attractiveness (Weitzman, 1979) in the case of internal testing. However, we find that the involvement of the external supplier, who accumulates private information, can reverse the optimal testing sequence under sequential prototyping. This is because the sequence of decreasing attractiveness can aggravate the supplier's strategic behavior: The supplier might not release the first prototype (the one preferred by the manufacturer), since she is speculating on a lower cost and hence a higher profit margin for the second one. Therefore, unless the testing costs are very large (so that the manufacturer would never test the second prototype if the first one succeeds), the manufacturer should consider testing the less attractive prototype first, as Figure 4 on page 18 illustrates. In other words, if a manufacturer develops prototypes internally (no information asymmetry), it is always optimal to test the higher margin design first. But if a manufacturer delegates the prototype development to an external supplier, it can be optimal to reverse the sequence and start by testing the lower margin design.

We also find that the classical target costing approaches (cost- and market-based) need to be adjusted in the presence of alternative designs if tested sequentially. Due to the strategic non-release behavior of suppliers, it is not always optimal to provide identical target costs for designs with similar cost and performance estimates or different target costs for dissimilar designs, as shown in Figure 3 on page 17. For example, if the designs have identical cost and performance estimates, the target costs for the first prototype should be set higher to avoid the supplier's strategic non-release behavior and to avoid the risk of not obtaining a successful prototype. There are also parameter constellations in which very different designs can have equal target costs.

Finally, committing to carefully chosen target costs upfront reduces the supplier's strategic behavior and is preferable for the manufacturer for a wide range of cases, as shown in Figure 6 on page 25. However, if one prototype features exceptionally high performance, the manufacturer can take advantage of the supplier's strategic behavior by remaining flexible and specifying the second prototype's target costs only after the first one has been tested (or not released). Doing so can sometimes push suppliers to strategically release prototypes that are not profitable to them (or that are below an acceptable level of profitability).

We acknowledge that our paper has several limitations. The comparison of manufacturer profits between the commitment scheme and the flexible scheme cannot be done analytically, and hence we use numerical studies to confirm the generality of our results. Furthermore, our model is restricted to two prototypes and assumes no learning between designs (similar to the early testing literature). While this adequately captures those scenarios where the manufacturer wants to test a few very different designs, it is not very applicable to scenarios in which many closely related design alternatives are being tested.

This research demonstrates that information asymmetry resulting from the involvement of an external supplier can have a profound impact on the traditional approaches to testing and prototyping. This effect should by no means be limited to the target costing settings. Other contract types applicable to new product development, e.g., performance-contingent contracts, can have a substantially different influence on the incentive alignment between the parties. Furthermore, the effects of cross-design learning, supplier competition, component improvement possibilities, and many other factors are yet to be explored in greater detail. Finally, further research in the area will greatly benefit from empirical studies quantifying the impact of the information asymmetry on the benefits of collaborative design.

Appendix

Proof of Lemma 1

From (10) it follows that it is optimal for M to choose $a_m = D$ if

$$r_1 - w_1 + \alpha_2 \left((r_2 - w_2) - (r_1 - w_1)\right) \int_0^{w_1} G(\bar{c}_2^{(1)}) g(c_1 | h_2(1)) \, \mathrm{d}c_1 - 2K \geq r_1 - w_1 - K,$$

and to choose $a_m = nD$ otherwise. Equation (12) follows directly. □

Proof of Proposition 1

The threshold is found by finding the cost at which V is indifferent between releasing and not releasing the first prototype. This cost c_1 must satisfy $\alpha_1 \pi_v^*(\boldsymbol{s}|h_2(1)) + (1-\alpha_1)\pi_v^*(\boldsymbol{s}|h_2(0)) = \pi_v^*(\boldsymbol{s}|h_2(0))$, or equivalently, $\pi_v^*(\boldsymbol{s}|h_2(1)) = \pi_v^*(\boldsymbol{s}|h_2(0))$. Note that $\pi_v^*(\boldsymbol{s}|h_2(1))$ is continuous and decreasing in c_1, whereas $\pi_v^*(\boldsymbol{s}|h_2(0))$ is independent of c_1. Therefore, if there exists a c_1 such that $\pi_v^*(\boldsymbol{s}|h_2(1)) = \pi_v^*(\boldsymbol{s}|h_2(0))$, then this c_1 is the unique release threshold.

Solving $\pi_v^*(\boldsymbol{s}|h_2(1)) = \pi_v^*(\boldsymbol{s}|h_2(0))$ (separately for $a_m^* = nD$ and $a_m^* = D$), we obtain

$$\bar{c}_1 = w_1 - \pi_v^*(\boldsymbol{s}|h_2(0)) \tag{25}$$

if $a_m^* = nD$, and

$$\bar{c}_1 = \begin{cases} w_1 - \pi_v^*(\boldsymbol{s}|h_2(0)), & \text{if } w_2 - w_1 + \bar{c}_1 < 0 \\ \begin{cases} w_1 \\ w_1 + \frac{2(1-\alpha_2 w_2)}{\alpha_2} \end{cases}, & \text{if } 0 \le w_2 - w_1 + \bar{c}_1 \le 1 \\ w_1 - \frac{\alpha_2(1-w_2)^2}{2(1-\alpha_2)}, & \text{if } w_2 - w_1 + \bar{c}_1 > 1 \end{cases} \tag{26}$$

if $a_m^* = D$.

The next step is to rule out infeasible cases by substituting the value of $\bar{c}_1$ into the corresponding condition for $w_2 - w_1 + \bar{c}_1$ in equation (26) and verifying whether it holds. After ruling out infeasible scenarios based on this substitution, equations (25)–(26) simplify to (15). □

Proof of Proposition 2

Suppose $\widetilde{w}_a$ and $\widetilde{w}_b$ are jointly optimal for a given testing sequence (which is not necessarily optimal). Let $r_b - \widetilde{w}_b < r_a - \widetilde{w}_a$. Suppose M decides to develop prototype a first. From Lemma 1, it follows immediately that $\widetilde{a}_m = nD$, i.e., M stops the development if prototype a is successful. Then M's expected profit is given as follows:

$$\begin{aligned} &\pi_m(\widetilde{\boldsymbol{s}}) = \alpha_a G(\bar{c}_a)(r_a - \widetilde{w}_a - K) + (1 - \alpha_a G(\bar{c}_a))\alpha_b G(\widetilde{w}_b)(r_b - \widetilde{w}_b - 2K) \\ &= \alpha_a G(\widetilde{w}_a - \pi_v^*(\widetilde{\boldsymbol{s}}|h_2(0)))(r_a - \widetilde{w}_a) + \big(1 - \alpha_a G(\widetilde{w}_a - \pi_v^*(\widetilde{\boldsymbol{s}}|h_2(0)))\big)\alpha_b G(\widetilde{w}_b)(r_b - \widetilde{w}_b - K) - K. \end{aligned} \tag{27}$$

Assume that K is sufficiently small, specifically, that

$$K < \alpha_a \left((r_a - \widetilde{w}_a) - (r_b - \widetilde{w}_b)\right) \int_0^{\widetilde{w}_b} G(\bar{c}_a^{(1)}) g(c_b|h_2(1)) \, \mathrm{d}c_b. \tag{28}$$

Note that the right-hand side is strictly greater than 0, since $r_a - \widetilde{w}_a > r_b - \widetilde{w}_b$ and $\alpha_a, \widetilde{w}_b > 0$, which means there always exists a range of values of K satisfying (28).

Now suppose that M, while keeping the same target costs, changes the testing sequence so that prototype b is tested first and prototype a second. For sufficiently small K, as defined in (28), it always holds that $\hat{a}_m = D$ under the new testing sequence, and hence $\overline{c}_1 = w_1$. M's corresponding expected profit is then as follows:

$$\begin{aligned}\pi_m(\hat{\boldsymbol{s}}) &= \alpha_b G(\overline{c}_b)\big(r_b - \widetilde{w}_b + \alpha_a(r_a - \widetilde{w}_a - r_b + \widetilde{w}_b)\int_0^{\overline{c}_1} G(\widetilde{w}_a - \widetilde{w}_b + c)g(c|h_2(1))\,\mathrm{d}c - 2K\big) \\ &\qquad + (1 - \alpha_b G(\overline{c}_b))\alpha_a G(\widetilde{w}_a)(r_a - \widetilde{w}_a - 2K) \\ &= \alpha_b G(\widetilde{w}_b)\big(r_b - \widetilde{w}_b + \alpha_a(r_a - \widetilde{w}_a - r_b + \widetilde{w}_b)\int_0^{\widetilde{w}_b} G(\widetilde{w}_a - \widetilde{w}_b + c)g(c|h_2(1))\,\mathrm{d}c\big) \\ &\qquad + (1 - \alpha_b G(\widetilde{w}_b))\alpha_a G(\widetilde{w}_a)(r_a - \widetilde{w}_a) - 2K. \end{aligned} \tag{29}$$

Now we take the difference between the two expected profits under different testing sequences. First, for the case where $\widetilde{w}_a \geq \widetilde{w}_b$, which corresponds to $w_2 \geq w_1$ in (11), we have

$$\begin{aligned}&\pi_m(\hat{\boldsymbol{s}}|\widetilde{w}_a \geq \widetilde{w}_b) - \pi_m(\widetilde{\boldsymbol{s}}) \\ &\quad = \frac{1}{2}\alpha_a\alpha_b(\widetilde{w}_b)^2(r_b - \widetilde{w}_b)(1 - \alpha_b\widetilde{w}_b) - \frac{1}{2}\alpha_a\alpha_b\widetilde{w}_b\left(2\widetilde{w}_a - \alpha_b(\widetilde{w}_b)^2\right)K - (1 - \alpha_b\widetilde{w}_b)\,K. \end{aligned} \tag{30}$$

Note that for the case where $\widetilde{w}_a < \widetilde{w}_b$, the value of $\int_0^{w_1} G(w_2 - w_1 + c_1)g(c_1|h_2(1))\,\mathrm{d}c_1$ as given by (11) is greater than for the case where $\widetilde{w}_a \geq \widetilde{w}_b$. Since all other components of (29) are the same, this means that $\pi_m(\hat{\boldsymbol{s}}|\widetilde{w}_a < \widetilde{w}_b) > \pi_m(\hat{\boldsymbol{s}}|\widetilde{w}_a \geq \widetilde{w}_b)$.

From (30) and the fact that $\pi_m(\hat{\boldsymbol{s}}|\widetilde{w}_a < \widetilde{w}_b) > \pi_m(\hat{\boldsymbol{s}}|\widetilde{w}_a \geq \widetilde{w}_b)$, it follows that if K is sufficiently small, $\pi_m(\hat{\boldsymbol{s}}) > \pi_m(\widetilde{\boldsymbol{s}})$, irrespective of the relative values of $\widetilde{w}_a$ and $\widetilde{w}_b$. The exact condition for K derived from (30) is

$$K < \frac{\frac{1}{2}\alpha_a\alpha_b(\widetilde{w}_b)^2(r_b - \widetilde{w}_b)(1 - \alpha_b\widetilde{w}_b)}{\frac{1}{2}\alpha_a\alpha_b\widetilde{w}_b\left(2\widetilde{w}_a + \alpha_b(\widetilde{w}_b)^2\right) + (1 - \alpha_b\widetilde{w}_b)} \tag{31}$$

if $\frac{1}{2}\alpha_a\alpha_b\widetilde{w}_b\left(2\widetilde{w}_a - \alpha_b(\widetilde{w}_b)^2\right) + (1 - \alpha_b\widetilde{w}_b) > 0$, and K is unconstrained otherwise.

Therefore, if K is sufficiently small, i.e., both (28) and (31) hold, and M chooses the testing sequence such that $r_2 - \widetilde{w}_2 < r_1 - \widetilde{w}_1$, where the $\widetilde{w}_i$ are optimal for the chosen sequence, M is always better off swapping the prototypes so that $r_2 - \widetilde{w}_2 > r_1 - \widetilde{w}_1$. This means that $r_2 - w_2^* \geq r_1 - w_1^*$, where the w_i^* are the optimal target costs for the optimal testing sequence. □

Proof of Proposition 3

We first derive the conditions under which each of the four possible combinations of V's actions are optimal:

1. **Release neither.** $a^*_{v,a} = nR_a$ and $a^*_{v,b} = nR_b$ are jointly optimal if and only if $c_b > w_b$ and $c_a > w_a$. Proof:

   - If both conditions hold, $\overline{\overline{\pi}}_v(R_a, nR_b), \overline{\overline{\pi}}_v(nR_a, R_b), \overline{\overline{\pi}}_v(R_a, R_b) < 0 = \overline{\overline{\pi}}_v(nR_a, nR_b)$, and thus $a^*_{v,a} = nR_a$ and $a^*_{v,b} = nR_b$ are optimal.
   - If $c_b \leq w_b$, then $\overline{\overline{\pi}}_v(nR_a, R_b) > 0 = \overline{\overline{\pi}}_v(nR_a, nR_b)$, and thus $a_{v,a} = nR_a$ and $a_{v,b} = nR_b$ are not optimal.
   - If $c_a \leq w_a$, then $\overline{\overline{\pi}}_v(R_a, nR_b) > 0 = \overline{\overline{\pi}}_v(nR_a, nR_b)$, and thus $a_{v,a} = nR_a$ and $a_{v,b} = nR_b$ are not optimal.

2. **Release *a* only.** $a^*_{v,a} = R_a$ and $a^*_{v,b} = nR_b$ are jointly optimal if and only if $c_b > w_b$ and $c_a \leq w_a$. Proof:

   - If both conditions hold, $\overline{\overline{\pi}}_v(nR_a, R_b) < 0$. From (18), it follows that $\overline{\overline{\pi}}_v(R_a, R_b) = \overline{\overline{\pi}}_v(R_a, nR_b) + (1 - \alpha_a)\overline{\overline{\pi}}_v(nR_a, R_b)$. As $\overline{\overline{\pi}}_v(nR_a, R_b) < 0$, this means that $\overline{\overline{\pi}}_v(R_a, nR_b) > \overline{\overline{\pi}}_v(R_a, R_b) > 0 > \overline{\overline{\pi}}_v(nR_a, R_b)$. Therefore, $a^*_{v,a} = R_a$ and $a^*_{v,b} = nR_b$ are optimal.
   - If $c_b \leq w_b$, then $\overline{\overline{\pi}}_v(R_a, nR_b) \leq \overline{\overline{\pi}}_v(R_a, R_b)$ and thus $a_{v,a} = R_a$ and $a_{v,b} = R_b$ are optimal, so $a_{v,a} = R_a$ and $a_{v,b} = nR_b$ are not optimal.
   - If $c_a > w_a$, then $\overline{\overline{\pi}}_v(R_a, nR_b) < 0$, i.e., the strategy of not releasing any prototype dominates $a_{v,a} = R_a$ and $a_{v,b} = nR_b$, and thus $a_{v,a} = R_a$ and $a_{v,b} = nR_b$ are not optimal.

3. **Release both.** $a^*_{v,a} = R_a$ and $a^*_{v,b} = R_b$ are jointly optimal if and only if $c_b \leq w_b$ and $c_a \leq w_a - \overline{\overline{\pi}}_v(nR_a, R_b)$. Proof:

   - If both conditions hold, it is straightforward that $\overline{\overline{\pi}}_v(R_a, R_b) \geq \overline{\overline{\pi}}_v(R_a, nR_b) > 0$. To see that $\overline{\overline{\pi}}_v(R_a, R_b) \geq \overline{\overline{\pi}}_v(nR_a, R_b)$, consider that $\overline{\overline{\pi}}_v(R_a, R_b) - \overline{\overline{\pi}}_v(nR_a, R_b) = \alpha_a(w_a - \overline{\overline{\pi}}_v(nR_a, R_b) - c_a) \geq 0$, as $c_a \leq w_a - \overline{\overline{\pi}}_v(nR_a, R_b)$. Therefore, $a^*_{v,a} = R_a$ and $a^*_{v,b} = R_b$ are optimal.

- If $c_b > w_b$, then $\overline{\overline{\pi}}_v(R_a, R_b) < \overline{\overline{\pi}}_v(R_a, nR_b)$, and thus $a_{v,a} = R_a$ and $a_{v,b} = R_b$ are not optimal.
- If $c_a > w_a - \overline{\overline{\pi}}_v(nR_a, R_b)$, then $\overline{\overline{\pi}}_v(R_a, R_b) < \overline{\overline{\pi}}_v(nR_a, R_b)$, and thus $a_{v,a} = R_a$ and $a_{v,b} = R_b$ are not optimal.

4. **Release b only.** $a^*_{v,a} = nR_a$ and $a^*_{v,b} = R_b$ are jointly optimal if and only if $c_b \leq w_b$ and $c_a > w_a - \overline{\overline{\pi}}_v(nR_a, R_b)$. Proof by exclusion.

Now we combine the derived conditions to formulate release rules for the supplier. First, $a^*_{v,b} = R_b$ is optimal (irrespective of $a^*_{v,a}$) if $c_b \leq w_b$. Second, $a^*_{v,a} = R_a$ is optimal (irrespective of $a^*_{v,b}$) if either of the following holds: (i) $c_b > w_b$ and $c_a \leq w_a$, or (ii) $c_b \leq w_b$ and $c_a \leq w_a - \overline{\overline{\pi}}_v(nR_a, R_b)$. Note that $c_b \leq w_b$ is equivalent to $\overline{\overline{\pi}}_v(nR_a, R_b) \geq 0$. Therefore, the conditions from the two cases can be combined into one condition: $c_a \leq w_a - \overline{\overline{\pi}}_v(nR_a, R_b)^+$, where $\overline{\overline{\pi}}_v(nR_a, R_b)^+ = \max\{\overline{\overline{\pi}}_v(nR_a, R_b), 0\}$. □

Proof of Proposition 4

Consider a pair of optimal target costs for parallel testing, $\hat{w}_a$ and $\hat{w}_b$, and label the prototypes so that $r_a - \hat{w}_a \geq r_b - \hat{w}_b$. Therefore,

$$\overline{\overline{\pi}}_m = \hat{w}_b \left(\left[\hat{w}_a - \alpha_b \frac{\hat{w}_b}{2} \right]^+ \alpha_a (r_a - \hat{w}_a) + \left(1 - \left[\hat{w}_a - \alpha_b \frac{\hat{w}_b}{2} \right]^+ \right) \alpha_b (r_b - \hat{w}_b) \right) + (1 - \hat{w}_b) \hat{w}_a \alpha_a (r_a - \hat{w}_a) - 2K. \quad (32)$$

Now consider the scenario in which M tests the prototypes using the same target costs but tests them sequentially. Let's first consider the case where

$$\alpha_a \left((r_a - \hat{w}_a) - (r_b - \hat{w}_b) \right) \int_0^{\hat{w}_b} G(\bar{c}_a^{(1)}) g(c_b | h_2(1)) \, \mathrm{d}c_b \geq K$$

(which includes the case of $K = 0$), and suppose that M tests prototype b first, i.e., $a^*_m = D$. In this case, V releases prototype b if $c_b \leq \hat{w}_b$. If prototype b is feasible ($c_b \leq \hat{w}_b$), she releases prototype a only if $\hat{w}_a - c_a \geq \hat{w}_b - c_b$ or, equivalently, $c_a \leq \hat{w}_a - \hat{w}_b + c_b$, and if prototype b is infeasible, she releases prototype a if $c_a \leq \hat{w}_a$. These conditions can be simplified to: $c_a \leq \hat{w}_a - [\hat{w}_b - c_b]^+$. Note that $\int_0^1 \left(\hat{w}_a - [\hat{w}_b - c_b]^+ \right) g(c_b) \, \mathrm{d}c_b = \hat{w}_a - \int_0^{\hat{w}_b} (\hat{w}_b - c_b) g(c_b) \, \mathrm{d}c_b = \hat{w}_a - \frac{\hat{w}_b}{2}$. We denote the corresponding manufacturer profit as π_1 and rewrite it as

$$\pi_1 = \alpha_b \hat{w}_b \left[\left[\hat{w}_a - \frac{\hat{w}_b}{2} \right]^+ \alpha_a (r_a - \hat{w}_a) + \left(1 - \left[\hat{w}_a - \frac{\hat{w}_b}{2} \right]^+ \right) (r_b - \hat{w}_b) \right] + (1 - \alpha_b \hat{w}_b) \hat{w}_a \alpha_a (r_a - \hat{w}_a) - 2K. \quad (33)$$

We now need to consider 3 subcases:

(i) Suppose $\hat{w}_a \geq \frac{\hat{w}_b}{2} \geq \frac{\alpha_b \hat{w}_b}{2}$. Taking the difference between (33) and (32), we obtain: $\pi_1 - \overline{\overline{\pi}}_m = \alpha_b \hat{w}_b (1 - \alpha_b)(r_b - \hat{w}_b) \frac{\hat{w}_b}{2} > 0$.

(ii) Suppose $\frac{\hat{w}_b}{2} > \hat{w}_a > \frac{\alpha_b \hat{w}_b}{2}$. Taking the difference between (33) and (32), we obtain: $\pi_1 - \overline{\overline{\pi}}_m = \frac{\alpha_b \hat{w}_b}{4} ((r_b - \hat{w}_b)(\hat{w}_a - \frac{\alpha_b \hat{w}_b}{2}) + \alpha_a (r_a - \hat{w}_a)(\frac{\hat{w}_b}{2} - \hat{w}_a)) > 0$.

(iii) Suppose $\hat{w}_a < \frac{\alpha_b \hat{w}_b}{2}$. Taking the difference between (33) and (32), we obtain: $\pi_1 - \overline{\overline{\pi}}_m = \alpha_a (1 - \alpha_b) \hat{w}_a \hat{w}_b (r_a - \hat{w}_a) > 0$.

Thus, in all three cases, sequential prototyping strictly dominates parallel prototyping.

Now consider the case where

$$\alpha_a \left((r_a - \hat{w}_a) - (r_b - \hat{w}_b) \right) \int_0^{\hat{w}_b} G(\overline{c}_a^{(1)}) g(c_b | h_2(1)) \, \mathrm{d}c_b < K,$$

and suppose that the manufacturer tests prototype a first, i.e., $a_m^* = nD$.

In this case, the supplier releases prototype a if $c_a \leq \hat{w}_a$. If prototype a is feasible, she does not release prototype b, and if it is infeasible she releases prototype b if $c_b \leq \hat{w}_b$. We denote the manufacturer profit in this case as π_2, and we rewrite it as

$$\pi_2 = \alpha_a \hat{w}_a \left[r_a - \hat{w}_a - K \right] + (1 - \alpha_a \hat{w}_a) \left[\hat{w}_a \alpha_b (r_b - \hat{w}_b) - 2K \right]. \quad (34)$$

This time we need to consider 2 subcases, as the maximum operator is present only in (32):

(i) Suppose $\hat{w}_a \geq \frac{\alpha_b \hat{w}_b}{2}$. Taking the difference between (34) and (32), we obtain:

$$\pi_2 - \overline{\overline{\pi}}_m = \alpha_b \hat{w}_b \left((1 - \alpha_a) \hat{w}_a (r_b - \hat{w}_b) + \alpha_a \frac{\hat{w}_b}{2} (r_a - \hat{w}_a) - \frac{\alpha_b \hat{w}_b}{2} (r_b - \hat{w}_b) \right) + \left(1 + (1 - \alpha_a \hat{w}_a)(1 - 2\alpha_b \hat{w}_b) \right) K > 0.$$

Note that in the above equation, both $\hat{w}_a (r_b - \hat{w}_b)$ and $\frac{\hat{w}_b}{2} (r_a - \hat{w}_a)$ are greater than or equal to $\frac{\alpha_b \hat{w}_b}{2} (r_b - \hat{w}_b)$, and therefore their weighted average (with α_a as the weight) is greater than or equal to $\frac{\alpha_b \hat{w}_b}{2} (r_b - \hat{w}_b)$.

(ii) Suppose $\hat{w}_a < \frac{\alpha_b \hat{w}_b}{2}$. Taking the difference between (34) and (32), we obtain:

$$\pi_2 - \overline{\overline{\overline{\pi}}}_m = \alpha_a \hat{w}_a \hat{w}_b (r_a - \hat{w}_a - \alpha_b(r_b - \hat{w}_b)) + (1 + (1 - \alpha_a \hat{w}_a)(1 - 2\alpha_b \hat{w}_b))\, K > 0.$$

Hence in this case as well, sequential prototyping strictly dominates parallel prototyping. □

Proof of Proposition 5

To find the first-period release threshold for the case $a^*_{mf} = D$, we solve $\pi^*_{vf}((s_{vf}, s_{mf})|h_3(D)) = \pi^*_{vf}((s_{vf}, s_{mf})|h_2(0))$ for c_1:

$$w_{1f} - c_1 + \alpha_2 \int_0^{\overline{c}_2^{(1)}} \left((w_{2f}^{(1)} - c_2) - (w_{1f} - c_1)\right) g(c_2)\,\mathrm{d}c_2 = \frac{\alpha_2 \left(w_{2f}^{(0)}\right)^2}{2}, \tag{35}$$

where $\int_0^{\overline{c}_2^{(1)}} \left((w_{2f}^{(1)} - c_2) - (w_{1f} - c_1)\right) g(c_2)\,\mathrm{d}c_2 = \begin{cases} 0, & \text{if } \overline{c}_{2f}^{(1)} < 0 \\ \frac{\left(w_{2f}^{(1)} - w_{1f} + c_1\right)^2}{2}, & \text{if } 0 \le \overline{c}_{2f}^{(1)} \le 1 \\ w_{2f}^{(1)} - \frac{1}{2} - w_{1f} + c_1, & \text{if } \overline{c}_{2f}^{(1)} > 1. \end{cases}$

First, if $w_{2f_1}^{(1)*} = w_{1f} + 1 - \overline{c}_{1f}$, then

$$\overline{c}_{1f_1} = w_{1f} + \frac{\alpha_2}{2} - \pi^*_{vf}((s_{vf}, s_{mf})|h = 0). \tag{36}$$

Second, if $w_{2f_2}^{(1)*} = w_{1f} + \frac{r_2 - r_1}{2} - \frac{\overline{c}_{1f}}{4}$, then

$$\overline{c}_{1f_2} = \frac{2}{9} \cdot \frac{8 + 3\alpha_2(r_2 - r_1) + 4\sqrt{4 - 3\alpha_2(r_2 - r_1) - \frac{9}{2}\alpha_2 \left(w_{1f} - \pi^*_{vf}((s_{vf}, s_{mf})|h_2(0))\right)}}{\alpha_2}. \tag{37}$$

We can further show that $w_{2f_2}^{(1)*} < w_{2f_1}^{(1)*}$ for all feasible w_1. To see this, consider

$$w_{2f_1}^{(1)*} - w_{2f_2}^{(1)*} = \frac{1}{72\alpha_2}\left(72\alpha_2 - 36\alpha_2^2 + M + 4\sqrt{32 + M}\right), \tag{38}$$

where $M = 32 + \alpha_2\left(48(r_1 - r_2) + 9\alpha_2 r_2^2 - 72 w_1\right)$. Because $w_1 \le r_1$, (38) is always positive.

From the fact that $w_{2f_2}^{(1)*} < w_{2f_1}^{(1)*}$ it follows that

$$w_{2f}^{(1)*} = \left(w_{1f} + \min\left\{\frac{r_2 - r_1}{2} - \frac{\widetilde{c}_{1f}}{4}, 1 - \widetilde{c}_{1f}\right\}\right)^+ = \left(w_{1f} + \frac{r_2 - r_1}{2} - \frac{\widetilde{c}_{1f_2}}{4}\right)^+.$$

If $a^*_{mf} = nD$, we solve $\alpha_1(w_1 - c_1) + (1 - \alpha_1)\pi^*_{vf}((s_{vf}, s_{mf})|h_2(0)) = \pi^*_{vf}((s_{vf}, s_{mf})|h_2(0))$ for c_1 to find the first-period release threshold:

$$\overline{c}_{1f_3} = w_{1f} - \pi^*_{vf}((s_{vf}, s_{mf})|h_2(0)). \tag{39}$$

Now we formalize the first-period supplier release threshold:

$$\bar{c}_{1f} = \begin{cases} w_{1f} - \pi^*_{vf}(\boldsymbol{s}_f | h_2(0)), & \text{if } a^*_m = nD \\ \frac{2}{9} \cdot \frac{8+3\alpha_2(r_2-r_1)+4\sqrt{4-3\alpha_2(r_2-r_1)-\frac{9}{2}\alpha_2\left(w_{1f}-\pi^*_{vf}(\boldsymbol{s}_f|h_2(0))\right)}}{\alpha_2}, & \text{if } a^*_m = D. \end{cases} \tag{40}$$

□

Proof of Corollary 1

Note that for the case $a^*_m = D$, $w^{(1)*}_{2f} > 0$ must hold because otherwise the manufacturer does not test the second prototype. For $\bar{c}_{1f_2}$, this condition is equivalent to $w_{1f} \geq \frac{2-4\alpha_2(r_2-r_1)-\sqrt{4+\alpha_2^2 r_2^2}}{6\alpha_2}$ (this follows from solving $w^{(1)*}_{2f} > 0$). Solving $\bar{c}_{f_2} > w_{1f}$ for w_{1f}, we obtain two regions: (1) $w_{1f} < \frac{2}{3}r_1 - \frac{4}{3}r_2$ (which never holds for $w_{1f} \geq \frac{2-4\alpha_2(r_2-r_1)-\sqrt{4+\alpha_2^2 r_2^2}}{6\alpha_2}$) and (2) $w_{1f} > \frac{2}{3}r_1$. Therefore, $\bar{c}_{1f_2} > w_{1f}$ if $w_{1f} > \frac{2}{3}r_1$, and the reverse holds if $w_{1f} < \frac{2}{3}r_1$.

Trivially, $\bar{c}_{1f_3} = w_{1f} - \pi^*_{vf}((s_{vf}, s_{mf})|h_2(0)) < w_{1f}$.

Combining the above results, if $\Big((r_2 - w^{(1)*}_{2f}) - (r_1 - w_{1f})\Big)\mathrm{Pr}_{success,f} \geq K$ (i.e., $a^*_m = D$) and $w_{1f} > \frac{2}{3}r_1$, then $\bar{c}_{1f} > w_{1f}$. Otherwise, $\bar{c}_{1f} \leq w_{1f}$. □

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