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Multihoming vs. Single-Homing Software: Compatibility or Competition?

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ABSTRACT Compatibility or competition is a key strategic decision for multihoming software developers. Compatibility is a strategy by which companies set up their software to be more compatible with their competitors' products, while competition is an opposite strategy by which the companies set up their software without any compatibility. We study the strategic decision of a multihoming software company that competes with two firms on different operating systems, (such as Windows and Mac). By formalizing a game-theoretic model to capture the motivation of a multihoming software developer, we find that the compatibility strategy is mainly incentivized by the trade-off between the spillover effect and the compatibility cost. We then solve for reasonable software prices and compatibility level given the market potential from the software firms' perspective. Several managerial guidelines are obtained to determine the optimal decision in the software development economy. Interestingly, when both the spillover effect and the compatibility cost are low enough, the multihoming software firm still chooses the competing strategy. Finally, by reporting the numerical analysis, we verify the effectiveness of the theoretical results derived in our model.

INDEX TERMS Software development management, compatibility, profitability, spillover effect.

I. INTRODUCTION

As IT and mobile technologies developed, it was easier for software consumers to use different operating systems in different scenarios. For example, consumers may use Microsoft Windows in the office but a Mac operating system at home. Consumers may also use computers at work but mobile systems for convenience or emergencies. For their users, software firms may develop different versions of software on different competing operating systems. Following the work of [1] and [2], we call such consumers, software, and firms multihoming users, multihoming software, and multihoming firms, respectively. In contrast to multihoming firms, some firms make their software available on only one operating system; these firms are referred to as single-homing firms. Microsoft Visio is typical single-homing software that only works on Windows systems, while Microsoft Word and Excel are multihoming programs that work under both the Windows and Mac operating systems. Visio's competitor, Edraw, professional drawing software available in China, has both Windows and Mac versions.

We are motivated by cases in which a multihoming firm may make its software compatible with that of its competitor. Software compatibility always refers to the capability of specific software to run on a particular CPU architecture or operating system, which means that it is compatible with the hardware. In this research, however, software compatibility is different from that mentioned above; instead, it refers to compatibility between competing software products. Taking the drawing software market for example, Edraw is multihoming, with a Windows version and a Mac version, but Microsoft Visio and OmniGraffle are single-homing, with a Windows version and a Mac version, respectively. Edraw is compatible with Visio but is not compatible with OmniGraffle. Because Edraw is compatible with Visio, it obtains a competitive advantage under the Mac operating system, which is called

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a compatibility effect. However, it loses some demand under the Windows operating system, which is a spillover effect. Considering that when some multihoming consumers use Edraw to create a file on the Mac operating system first and then want to reopen it on the Windows operating system, if Edraw is incompatible with Visio, the only way to reopen it is to use Edraw (version for the Windows operating system) again; otherwise, if Edraw is compatible with Visio, there would be consumers who would reopen it easily using Visio. Therefore, it is less obvious why Edraw would have any motivation to be compatible with Visio. The compatibility level is a detail for the multihoming software producer to consider in its compatibility strategy [3]. A high compatibility level means that a file created by the multihoming software requires less reedit work when opened by the mature software under the major or traditional operating system. For example, a file created by Edraw might have some font or line weight changes when opened with Microsoft Visio.

A few unique features associated with the multihoming software economy make this context distinct from traditional economies. First, although software competition is not a new business model, multihoming and compatibility strategies make this competition more complicated. Multihoming software is compatible with the same software under the traditional operating system. The compatibility level is hard to decide, since it affects both the compatibility cost and the competitive advantage with the single-homing software under the emerging operating system. Therefore, how to use the compatibility advantage to persuade more users to acquire the product to achieve the optimal profit is a key issue multihoming firms face.

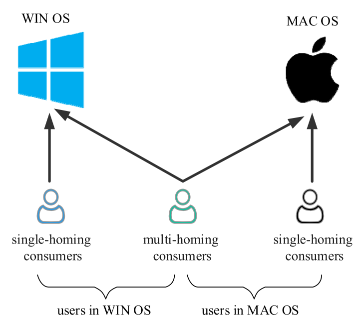

FIGURE 1. **Consumers on different operating systems.**

Second, based on the number of operating systems used by consumers, consumers are divided into multihoming consumers and single-homing consumers, as shown in Fig. 1. If the multihoming firm adopts a compatibility strategy, some multihoming consumers will use the multihoming software under the emerging operating system, which would shift to the mature or common software under the traditional operating system, which is referred to as the spillover effect in the software economy. The consumers gained by the compatibility effort may lose under the traditional operating system; thus multihoming firms face another key issue concerning how the spillover effect affects their compatibility strategy. For the mature firm under the traditional operating system, multihoming firms' compatibility strategy offers a free ride. A main question for the mature firm is whether to adopt a single-homing strategy to enjoy the convenience of the spillover effect or a multihoming strategy to compete with the multihoming software under the emerging operating system.

Third, the compatibility level and the spillover effect further complicate pricing decisions. Both the multihoming firm and the mature firm make decisions based on the optimal profit, which is affected by the number of consumers. Moreover, consumers under both operating systems choose software based on convenience and familiarity, which are affected by the compatibility level. Therefore, each firm must consider not only the matching of its own demand but also its competitors' strategies when setting software price.

We aim to explain the rationale for the multihoming firm's compatibility and the single-homing firm's multihoming strategy. Based on the software competition case, this article addresses the following questions: How does the spillover effect affect the multihoming firm that adopts the compatibility strategy and the single-homing firm that adopts the multihoming strategy? What is the impact of the compatibility strategy on the software's pricing strategy? Finally, how do software firms' profits change?

To answer the aforementioned questions, we formalize a game-theoretic model to capture the key tradeoffs that arise when a multihoming firm decides to adopt the compatibility strategy, and we consider a multihoming software firm competing with two other software firms on different operating systems. There are three types of consumers: multihoming, single-homing with a traditional operating system, and single-homing with an emerging operating system. To delineate the effect of compatibility, we first consider the scenario in which a multihoming firm makes its software incompatible with single-homing firms. Then, we consider the scenario in which a multihoming firm makes its software incompatible with a single-homing firm and both the direct effect and spillover effect of compatibility. The optimal strategy is derived by comparing the incompatibility case with the compatibility case.

Our findings highlight two key theoretical implications. First, the fundamental difference is attributable to the competition in the software economy and the realization of firms that cooperate under the traditional operating system but compete under the emerging operating system. The constrained price competition, as in the multihoming software economy, is less intense than the unconstrained price competition in standard software markets. Second, the competition in the software market and that in games is similar because firms choose strategies and then compete on price. However, our findings relate to the comparison of the spillover effect and the compatibility cost. Only when the spillover effect is not high and the compatibility cost is high enough can multihoming firms adopt the compatibility strategy and mature firms in the traditional market enter the emerging market at the same time. In this case, the firms have little incentive to compete on prices; rather, they are incentivized to be compatible with the industry leader to ease competition.

The rest of the paper proceeds as follows. Section 2 identifies the most related literature. In Section 3, we present the setup for our baseline model. Equilibrium results under compatibility and multihoming strategies are reported in Section 4. In Section 5, we compare the equilibrium outcomes and derive the conditions under which each strategy is the best for the multihoming firm. In Section 6, we offer concluding thoughts.

II. LITERATURE REVIEW

Our paper is related to a stream of literature on developer decisions in a multiplatform context. For instance, Ku and Cho performed an empirical study of 245 ERP software developers to identify the determinants of complementary platform selections [4]. Jonnalagedda and Saranga examined commonality decisions in manufactured product design for multiple markets [5]. Bresnahan, Orsini, and Yin empirically estimated user preferences and developer profitability [6]. Cattani and Heese investigated the offering strategy of two complementary products when competition exists between two firms that focus on different markets [7]. Liu *et al.* analyzed the impact of conversion technologies in IT markets with network effects [8]. The multihoming strategy shows the software competition and collaboration in development. Competition and collaboration in the software economy has many other forms, such as codevelopment [9], mergers and acquisitions [10], premium service [11], and product compatibility [12], [13]. However, departing from their study, our analytical model assumes that a software firm has already chosen its product offering strategies and focuses on the multihoming firm's compatibility strategy in the competition, while only the dominant firm under the traditional operating system decides whether to choose multihoming.

Our paper is also related to a stream of literature on the spillover effect in the context of technological progress. It is common for positive and negative spillover effects to occur in a market with technological progress. For instance, Li and Agarwal found positive spillover effects in both complementary and substitute markets [14]. In contrast, Fong *et al.* showed that targeted promotions can effectively reduce consumer search activities and leads to a negative spillover effect on cross-firm purchase activity [15]. It is also common for the spillover effect to occur alongside technological progress such as drug research & development [16], big data knowledge [17], technology-based financial support systems [18], the finance and real estate industry [19], and especially in the IT market [10]. We investigate the spillover effect in the software competition economy; furthermore, we investigate how the spillover effect affects the compatibility and multihoming strategies the software firms adopt.

Another related stream of literature explores product compatibility. Firms that introduce product compatibility can benefit from behavior-based pricing. Doganoglu and Wright examined the difference between multihoming and compatibility and found that the latter reduced incentives to pursue the former [20]. Maruyama and Zennyo found that compatibility depended on product lifecycles; once most users have purchased hardware, platform firms' profits accrue largely from content purchases, whereupon competing platform firms have incentives to become compatible [21]. Casadesus-Masanell and Ruiz-Aliseda, for example, explained large platform firms' preference for incompatibility in terms of the quest for market dominance [22], and Viecens showed that compatibility will always be preferred by a platform firm with smaller standalone value and never by its competitor [23]. Several studies in this literature examined compatibility incentives where one firm has a larger installed base (e.g., [24]–[27]) and found that it is less willing to be compatible because, with compatibility, it has to share its network, while with incompatibility, it can maintain its market dominance. Dou found, in a model with vertically differentiated platforms and content, that when an inferior platform firm owns premium content, it is optimal for the inferior platform firm to offer such content to a superior platform firm [28]. Dou's paper assumes that one-way compatibility can be established without the rival's permission. In our model, we consider one-way compatibility but also the compatibility level. For example, Edraw is compatible with Microsoft Visio; files created by Edraw under Mac OS can be opened and edited by Microsoft Visio under Windows OS, but the fonts and line weights change slightly.

III. MODEL

In this section, we develop a model that we use to analyze the multihoming firm's compatibility decision compared with that of the single-homing firm. We consider three software firms, Firm 1, Firm 2, and Firm 3, which sell substitutable software to consumers. Firm 1 is multihoming and offers two versions of its product. One is version W, which is available under a traditional operating system such as the Windows operating system; the other is version M, which is available on an emerging operating system, such as the Mac/Mobile operating system. Firm 2 offers common software on the traditional operating system and has the option to serve as single-homing or multihoming. Firm 3 is single-homing and offers a single version only on the emerging operating system. In the case of the professional drawing software market, Microsoft Visio only works on the Windows operating system, OmniGraffle only works on the Mac operating system, while Edraw works on both systems.

We consider two strategies, C and N, adopted by Firm 1, where C is the compatibility strategy and N stands for the incompatibility strategy. Under strategy C, multihoming Firm 1's software is compatible with Firm 2's software, which is common and mature under the traditional operating system. In other words, a file created by Firm 1's software can be opened and edited by Firm 2's software and vice versa. Under strategy N, multihoming Firm 1's software is not compatible with any other firms' software, which means a file created by Firm 1's software can only be opened and edited by

TABLE 1. Firms' strategy description.

Firm	Strategy Description
Firm 1 (Edraw)	Multihoming firm decides whether to be compatible with Firm 2
Firm 2 (Microsoft Visio)	Common firm under the traditional/major operating system decides whether to be multihoming
Firm 3 (OmniGraffle)	Single-homing firm's software only works under the emerging/minor operating system

Firm 1's software. We consider two strategies (M and S) adopted by Firm 2, where M is the multihoming strategy and S stands for the single-homing strategy. Under strategy S, Firm 2's software only works on the traditional operating system. Under strategy M, Firm 2's software works on both operating systems, which means that Firm 2 supports the emerging operating system. The result when Firm 1 makes its software compatible with Firm 3's software can be similarly derived; therefore, we only consider the former situation. Firms' strategies are shown in Table 1.

A. CONSUMER DEMAND

Consistent with the practice in many markets (e.g., the professional drawing software market), we distinguish three types of consumers:

"W&M-type" consumers. These consumers are multihoming and want to buy W and M versions. We denote the market for this type of consumer as I. In the professional drawing software example, these consumers have two computers (i.e., one is installed with the Windows operating system, and the other is installed with Mac OS). When using the two computers to draw a flowchart, they will buy two different versions to match the different operating systems.

"W-type" consumers. These consumers are single-homing and just want to buy version W. We denote the market of this type of consumer as II.

"M-type" consumers. These consumers are single-homing and just want to buy version M. We denote the market of this type of consumer as II.

1) INCOMPATIBILITY & SINGLE-HOMING

In the incompatible and single-homing case, considering that market I refers to consumers who want to buy both versions and given that Firm 1 and Firm 2 each offer a W version to compete with the other on the W operating system, Firm 1 and Firm 3 both offer an M version on the M operating system. Therefore, we follow established norms in the marketing and operations literature (e.g., [29], [30], and [31]); our demand function is as follows:

$$d_1^I = \underbrace{k + c - p_1 + p_2}_{demand\ in\ system\ W} + \underbrace{k + c - p_1 + p_3}_{demand\ in\ system\ M} \quad (1)$$

$$d_2^I = k - c - p_2 + p_1 \quad (2)$$

$$d_3^I = k - c - p_3 + p_1 \quad (3)$$

where d_i and p_i refer to the realized demand and prices for Firm i's product ($i = 1, 2, 3$) under market I, respectively. Without loss of generality, we assume that Firm 1 sets the same price for both versions. $k > 0$ is the market potential of market I, and $0 < c < k$ is the advantage if the consumers choose the multihoming software, for example to exert less effort to convert a file.

Because Firm 1 is multihoming and offers two versions of its product, Firm 1's demand function contains two parts; the first part, $k + c - p_1 + p_2$, is the demand for Firm 1's W version when competing with Firm 2 in market I. The second part, $k + c - p_1 + p_3$, is the demand for Firm 1's M version when competing with Firm 3 in market I.

In market II, consumers are single-homing and just want to buy version W. Given that Firm 1 and Firm 2 each offer a W version, we assume that the market demand for Firm 1 and Firm 2 is as follows:

$$d_1^{II} = a - p_1 + p_2 \quad (4)$$

$$d_2^{II} = a - p_2 + p_1 \quad (5)$$

where d_i^{II} refers to the realized demand for Firm i's product ($i = 1, 2$) under market II, and $a > 0$ denotes the potential of market II.

Under market III, consumers are single-homing and just want to buy version M. Given that Firm 1 and Firm 3 each offer an M version, we assume that the market demand for Firm 1 and Firm 3 is as follows:

$$d_1^{III} = r - p_1 + p_3 \quad (6)$$

$$d_3^{III} = r - p_3 + p_1 \quad (7)$$

where d_i^{III} refers to the realized demand for Firm i's product ($i = 1, 3$) under market III, and $r > 0$ denotes the potential of market III.

Based on the above analysis, the demand functions for Firm $i (i = 1, 2, 3)$ in the whole market under an incompatible and single-homing case are as follows:

$$d_1 = d_1^I + d_1^{II} + d_1^{III} \quad (8)$$

$$d_2 = d_2^I + d_2^{II} \quad (9)$$

$$d_3 = d_3^I + d_3^{III} \quad (10)$$

2) INCOMPATIBILITY & MULTIHOMING

In the incompatible and multihoming case, two multihoming firms exist (Firm 1 and Firm 2), and Firm 2 supports the emerging operating system. Considering market I (where consumers want to buy both versions), given that Firm 1 and Firm 2 each offer a W version to compete with the other under the W operating system, Firm 1 and Firm 3 both offer an M version under the M operating system, and our demand function is as follows:

$$d_1^I = \underbrace{k - p_1 + p_2}_{demand\ in\ system\ W} + \underbrace{\frac{k + c}{2} - p_1 + \frac{p_2 + p_3}{2}}_{demand\ in\ system\ M} \quad (11)$$

$$d_2^I = \underbrace{k - p_2 + p_1}_{demand\ in\ system\ W} + \underbrace{\frac{k+c}{2} - p_2 + \frac{p_1+p_3}{2}}_{demand\ in\ system\ M} \tag{12}$$

$$d_3^I = k - c - p_3 + \frac{p_1+p_2}{2} \tag{13}$$

where d_i and p_i refer to the realized demand and prices for Firm 1's product ($i = 1, 2, 3$) under market I, respectively. Without loss of generality, we assume that Firm 1 sets the same price for both versions. $k > 0$ is the market potential of Market I, and $0 < c < k$ is the advantage if consumers choose the multihoming software, for example to exert less effort to convert a file.

Because Firm 1 and Firm 2 are multihoming and offer two versions of their products, both Firm 1's and Firm 2's demand functions contain two parts as shown in Equations (11) and (12), respectively.

Under market II, consumers are single-homing and just want to buy version W. Given that Firm 1 and Firm 2 each offer a W version, we assume that the market demands for Firm 1 and Firm 2 are as follows:

$$d_1^{II} = a - p_1 + p_2 \tag{14}$$

$$d_2^{II} = a - p_2 + p_1 \tag{15}$$

where d_i^{II} refers to the realized demand for Firm i's product ($i = 1, 2$) under market II and $a > 0$ denotes the potential of market II.

Under market III, consumers are single-homing and just want to buy version M. Given that all three firms offer an M version, we assume that the market demands for Firm 1, Firm 2, and Firm 3 are as follows:

$$d_1^{III} = \frac{2}{3}r - p_1 + \frac{p_2+p_3}{2} \tag{16}$$

$$d_2^{III} = \frac{2}{3}r - p_2 + \frac{p_1+p_3}{2} \tag{17}$$

$$d_3^{III} = \frac{2}{3}r - p_3 + \frac{p_1+p_2}{2} \tag{18}$$

where d_i^{III} refers to the realized demand for Firm i's product ($i = 1, 2, 3$) under market III and $r > 0$ denotes the potential of market III.

Based on the above analysis, the demand functions for Firm $i (i = 1, 2, 3)$ in the whole market under an incompatible and multihoming case are as follows:

$$d_1 = d_1^I + d_1^{II} + d_1^{III} \tag{19}$$

$$d_2 = d_2^I + d_2^{II} + d_2^{III} \tag{20}$$

$$d_3 = d_3^I + d_3^{III} \tag{21}$$

3) COMPATIBILITY & SINGLE-HOMING

In the compatible and single-homing case, files made by Firm 1's software can be opened and edited by Firm 2's software under the traditional operating system. Considering market I and the spillover effect [14], [15], [32], the market demand for Firm 1 and Firm 3 under the M system is as follows:

$$d_1^I = \underbrace{k + c - p_1 + p_2 - \overbrace{\beta(k + c - p_1 + p_3 + l)}^{spillovereffect}}_{demand\ in\ system\ W} + \underbrace{k + c - p_1 + p_3 + l}_{demand\ in\ system\ M} \tag{22}$$

$$d_2^I = k - c - p_2 + p_1 + \overbrace{\beta(k + c - p_1 + p_3 + l)}^{spillover\ effect} \tag{23}$$

$$d_3^I = k - c - p_3 + p_1 - l \tag{24}$$

where d_i and p_i refer to the realized demand and prices for Firm i's product ($i = 1, 2, 3$) under market I, respectively. Inspired by Ma et al. (2013), Firm 1's market demand can increase by the compatibility effort in the M system; therefore, $0 < l \leq k - c$ denotes the direct effect of compatibility on demand. $0 < \beta < 1$ denotes the spillover effect coefficient of compatibility. Firm 2's market demand can increase by the spillover effect in the W system so that consumers could use the common software under the traditional system. For example, in the case of the professional drawing software market, given that some multihoming consumers use Visio to create a file on the Windows operating system first and want to reopen and edit it on the Mac operating system, if Edraw is compatible with Microsoft Visio, they would likely have to reopen and edit the file using Edraw on the Mac operating system. We use l to capture such increasing demand. Furthermore, given that some multihoming consumers use Edraw to create a file on the Mac operating system first and want to reopen and edit it on the Windows operating system, if Edraw is incompatible with Visio, the only way to reopen it is to use Edraw (the Windows operating system version) again; otherwise, if Edraw is compatible with Visio, some consumers could reopen it easily using Visio. Therefore, we use $\beta(k + c - p_1 + p_3 + l)$ to capture such decreasing demand from the spillover effect.

Because Firm 1's compatibility strategy does not influence the single-homing consumers who only use the W operating system, the market demands for Firm 1 and Firm 2 under market II are as follows:

$$d_1^{II} = a - p_1 + p_2 \tag{25}$$

$$d_2^{II} = a - p_2 + p_1 \tag{26}$$

where d_i^{II} refers to the realized demand for Firm i's product ($i = 1, 2$) under market II.

Similarly, because Firm 1's compatibility strategy does not influence the single-homing consumers who only use the M operating system, the market demands for Firm 1 and Firm 3 under market III are as follows:

$$d_1^{III} = r - p_1 + p_3 \tag{27}$$

$$d_3^{III} = r - p_3 + p_1 \tag{28}$$

where d_i^{III} refers to the realized demand for Firm i's product ($i = 1, 3$) under market III.

Based on the above analysis, the demand functions for Firm $i(i = 1, 2, 3)$ in the whole market under the compatible and single-homing case are as follows:

$$d_1 = d_1^I + d_1^{II} + d_1^{III} \tag{29}$$
$$d_2 = d_2^I + d_2^{II} \tag{30}$$
$$d_3 = d_3^I + d_3^{III} \tag{31}$$

4) COMPATIBILITY & MULTIHOMING

In the compatible and multihoming case, considering market I, the spillover effect works and Firm 1 competes with Firm 2 under the M operating system. Therefore, the market demands for Firm 1 and Firm 3 on the M system are as follows:

$$d_1^I = \underbrace{k - p_1 + p_2 - \overbrace{\beta(\frac{k+c}{2} - p_1 + \frac{p_2+p_3}{2} + l)}^{spillover\ effect}}_{demand\ in\ system\ W} + \underbrace{\frac{k+c}{2} - p_1 + \frac{p_2+p_3}{2} + l}_{demand\ in\ system\ M} \tag{32}$$

$$d_2^I = \underbrace{k - p_2 + p_1 + \overbrace{\beta(\frac{k+c}{2} - p_1 + \frac{p_2+p_3}{2} + l)}^{spillover\ effect}}_{demand\ in\ system\ W} + \underbrace{\frac{k+c}{2} - p_2 + \frac{p_1+p_3}{2} + l}_{demand\ in\ system\ M} \tag{33}$$

$$d_3^I = k - c - p_3 + \frac{p_1+p_2}{2} - l \tag{34}$$

where d_i and p_i refer to the realized demand and prices for Firm ''s product $(i = 1, 2, 3)$ under market I, respectively.

Similarly, Firm 1's compatibility strategy does not influence the single-homing consumers who only use the W operating system; thus, the market demands for Firm 1 and Firm 2 under market II are as follows:

$$d_1^{II} = a - p_1 + p_2 \tag{35}$$
$$d_2^{II} = a - p_2 + p_1 \tag{36}$$

where d_i^{II} refers to the realized demand for Firm i 's product $(i = 1, 2)$ under market II.

Similarly, if Firm 2 adopts the multihoming strategy, the demands for the three firms under market III are as follows:

$$d_1^{III} = \frac{2}{3}r - p_1 + \frac{p_2+p_3}{2} \tag{37}$$
$$d_2^{III} = \frac{2}{3}r - p_2 + \frac{p_1+p_3}{2} \tag{38}$$
$$d_3^{III} = \frac{2}{3}r - p_3 + \frac{p_1+p_2}{2} \tag{39}$$

where d_i^{III} refers to the realized demand for Firm i's product $(i = 1, 2, 3)$ under market III.

Based on the above analysis, the demand functions for Firm $i(i = 1, 2, 3)$ in the whole market under the compatible and multihoming case are as follows:

$$d_1 = d_1^I + d_1^{II} + d_1^{III} \tag{40}$$
$$d_2 = d_2^I + d_2^{II} + d_2^{III} \tag{41}$$
$$d_3 = d_3^I + d_3^{III} \tag{42}$$

B. FIRM'S DECISION

For ease of exposition, we normalize that the multihoming development cost for Firm 2 is zero. In the incompatible case, we formulate firms' profits as follows:

$$\pi_i = p_i d_i, \quad i = 1, 2, 3 \tag{43}$$

where p_i, d_i are respectively price and demand for Firm $i(i = 1, 2, 3)$ in the incompatible case. Each firm chooses a price to maximize its profit.

In the compatible case, we formulate firms' profits as follows:

$$\pi_1 = p_1 d_1 - \frac{1}{2}\lambda\alpha^2 \tag{44}$$
$$\pi_i = p_i d_i, \quad i = 2, 3 \tag{45}$$

where are p_i, d_i respectively price and demand for Firm $i(i = 1, 2, 3)$ in the compatible case. Firm 1 needs to choose a compatibility level first; then, the firm chooses a price to maximize its profit. We assume Firm 1's compatibility cost is a quadratic function of compatibility level l, written as $\frac{1}{2}\lambda l^2$, where λ is the compatibility cost coefficient.

The time sequence of the game is as follows. In stage 1, Firm 1 proposes whether to make its software compatible with Firm 2's software; if it chooses the compatible strategy, it sets the compatibility level. In stage 2, firms price their software simultaneously. In stage 3, the consumers make their software purchase decisions. Fig. 2 illustrates the sequence of events, and Table 1 shows the notation used.

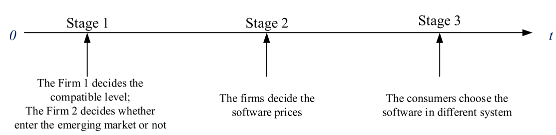

FIGURE 2. Sequence of events.

IV. EQUILIBRIUM ANALYSIS

In this section, we first analyze the firms' competition on compatibility and multihoming by deriving the equilibrium under each case. We then determine Firm 1's incentive for compatibility and Firm 2's for multihoming. Finally, we examine how the spillover effect affects the key equilibrium outcomes.

Lemma 1: Under the condition of $\lambda(8-2\beta)-(1-\beta)^2 > 0$, the profit functions given in 49 are cancave and have unique maxima.

Fig. 3 shows the variation of Firm 1's profit when compatibility level l increases for a given price p_1, a concave

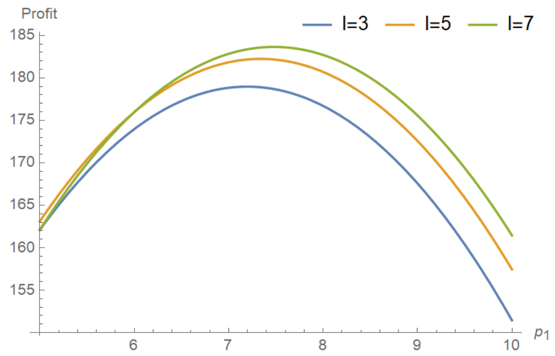

FIGURE 3. Firm 1's Profit changes with p_1.

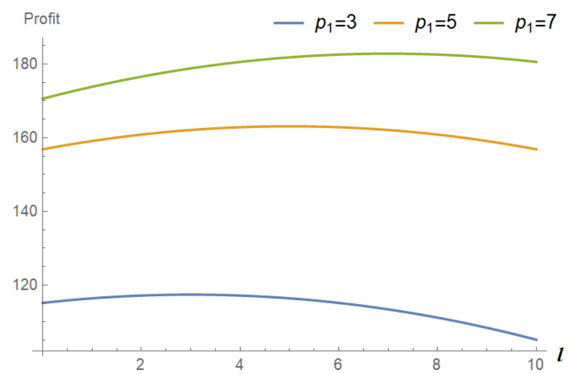

FIGURE 4. Firm 1's Profit changes with l.

function. We note from Fig. 2 that quoting a higher price may not be the optimal choice. Fig. 4 shows the variation of the profit function as Firm 1's software price p_1 is increased for a given l. The plot confirms that the profit function is concave. We also see that as p is increased for a given l, profit also increases. We also use these values for the exhaustive numerical analysis reported in Section VI.

In the next lemma, we obtain the closed-form solutions for our decision variables and for the equilibrium outcome.

Lemma 2: Under the condition in Lemma 1, all the equilibrium prices and profits are shown in Table 2.

Proposition 1: Under the condition in Lemma 1, the compatibility level positively relates to Firm 1's price, $\alpha = [(1-\beta)/\lambda]p_1$.

The two decision variables for Firm 1 are related no matter which strategy Firm 2 adopts. The price and compatibility level decided by Firm 1 are strategic and positively associated with each other, which can explain the strategy chosen in the next subsection.

Proposition 2: Under different cases, an increase in the spillover effect coefficient of the compatibility strategy (i.e., an increase in β) occurs when

(a) firm 1's profit first increases, then decreases with an increasing β;

(b) firm 2's profit first increases, then decreases with an increasing β.

TABLE 2. Notations.

Notation	Description
a	Market potential of traditional/major operating system
k	Market potential of multihoming consumers
r	Market potential of emerging/minor operating system
c	Disadvantage if consumer does not use multihoming software
p_i	Price of Firm i's software $(i=1,2,3)$
l	Compatibility level
β	Spillover effect parameter
λ	Compatibility cost parameter
π_i	Profit of Firm i, $(i=1,2,3)$

It is understandable that Firm 1's profit increases when the spillover effect is not too high, since Firm 1 could absorb more users from the M operating system. Moreover, Firm 1's profit decreases when the spillover effect is high enough that the profit of new users cannot offset the loss from spillover. Interestingly, the spillover effect has the same impact on Firm 2's profit. Intuitively, with the spillover effect, Firm 2 could take a free ride if Firm 1 adopts the compatibility strategy. However, if the spillover effect is high enough, to resist the loss of users under the W operating system, the compatibility level designed by Firm 1 would not be high. This phenomenon could also be seen in the equation of Proposition 1. The profit inflection points for the two firms are not the same with an increase in the spillover effect.

V. COMPATIBILITY & MULTIHOMING DECISION

Given the diverse compatibility & multihoming strategies found in the software supply chain, a key area of interest to the firms is one where a strategy is superior from their perspective. The area in question is especially interesting in light of the preceding section's findings that the equilibrium outcomes in all cases appear qualitatively similar.

A. STRATEGY PREFERENCES

Comparing Firm 1's profit achieved in the incompatible and compatible case, we obtain Proposition 3:

Proposition 3: When $\underline{\lambda}(\beta) \leq \lambda \leq \bar{\lambda}(\beta)$, Firm 1 chooses the compatibility strategy; otherwise, Firm 1 chooses the incompatibility strategy, where $\underline{\lambda}(\beta)$ and $\bar{\lambda}(\beta)$ yield the unique solution of $\pi_1^{N*} = \pi_1^{C*}$.

The compatibility and multihoming strategy preferences of the corresponding firms are shown in Fig.5. Proposition 3 states that the magnitude of spillover effect β and compatibility cost coefficient λ will alter Firm 1's compatibility strategy. To make the point more concrete, we illustrate the interactions between compatibility cost coefficientλ, spillover effect β, and the compatibility strategy choice for Firm 1 in Fig. 5. It is

TABLE 3. Equilibrium results.

	(N, SH)	(N, MH)	(C, SH)	(C, MH)
p_1	$\frac{3a+2c+6k+3r}{12}$	$\frac{12a+3c+21k+10r}{54}$	$\frac{1}{\beta(7-3\beta-10\lambda)+48\lambda-4}[\lambda(4(3a+2c+6k+3r)-\beta(3c+5k+r))]$	$\frac{1}{3(\beta(154-294\lambda-\beta(81-7\beta-25\lambda))+792\lambda-80)}[\lambda((528-84\beta)a+(132-102\beta+9\beta^2)c+(924-282\beta+15\beta^2)k+(440-88\beta+2\beta^2)r]$
p_2	$\frac{9a-4c+12k+3r}{24}$	$\frac{12a+3c+21k+10r}{54}$	$\frac{1}{2(\beta(7-3\beta-10\lambda)+48\lambda-4)}[2(1-\beta)(-(1+3\beta)\alpha+c-(1-4\beta)k+2\beta r)+\lambda(4(9-2\beta)a-(16-18\beta+3\beta^2)c+(48+14\beta-5\beta^2)k+(12+2\beta-\beta^2)r)]$	$\frac{1}{3(\beta(154-294\lambda-\beta(81-7\beta-25\lambda))+792\lambda-80)}[-((4(-1+\beta)(-21k-10r+3c(-1+\beta)+33k\beta+17r\beta+3a(-4+7\beta))+2(-22(3c+21k+10r)+66a(-4+\beta)+\beta(2r(23+\beta)+3c(-8+3\beta)+3k(16+5\beta)))\lambda)]$
p_3	$\frac{3a-4c+12k+9r}{24}$	$\frac{3a-6c+12k+7r}{27}$	$\frac{1}{\beta(7-3\beta-10\lambda)+48\lambda-4}[(1-\beta)(-3a-c-(7-2\beta)k-(4-\beta)r)+(6a+(24-5\beta)k-(8-\beta)c+3(6-\beta)r)\lambda]$	$\frac{1}{3(\beta(154-294\lambda-\beta(81-7\beta-25\lambda))+792\lambda-80)}[((1-\beta)(-8(39k+20r)+3c(-8+\beta)(-1+\beta)+(k(159-9\beta)-4r(-19+\beta))\beta+6a(-24+7\beta))+(-88(6c-12k-7r)+6a(44-9\beta)+3(c(69-7\beta)+5k(-21+\beta)+4r(-16+\beta))\beta)\lambda)]$
l	-	-	$\frac{1}{\beta(7-3\beta-10\lambda)+48\lambda-4}[(1-\beta)(4(3a+2c+6k+3r)-\beta(3c+5k+r))]$	$\frac{1}{3(\beta(154-294\lambda-\beta(81-7\beta-25\lambda))+792\lambda-80)}[(1-\beta)((528-84\beta)a+(132-102\beta+9\beta^2)c+(924-282\beta+15\beta^2)k+(440-88\beta+2\beta^2)r]$
π_1	$\frac{(3a+2c+6k+3r)^2}{36}$	$\frac{(12a+3c+21k+10r)^2}{729}$	$\frac{1}{2(\beta(7-3\beta-10\lambda)+48\lambda-4)^2}[(2(4-\beta)\lambda-(1-\beta)^2)\lambda(12a+(8-3\beta)c+(24-5\beta)k+(12-\beta)r)^2]$	$\frac{1}{18(\beta(154-294\lambda-\beta(81-7\beta-25\lambda))+792\lambda-80)^2}[(132(4a+c+7k)+440r-2(42a+51c+141k+44r)\beta+(9c+15k+2r)\beta^2)^2\lambda(-(1-\beta)^2+2(4-\beta)\lambda)]$
π_2	$\frac{(9a-4c+12k+3r)^2}{288}$	$\frac{(12a+3c+21k+10r)^2}{729}$	$\frac{1}{2(\beta(7-3\beta-10\lambda)+48\lambda-4)^2}[2(1-\beta)(-(1+3\beta)\alpha+c-(1-4\beta)k+2\beta r)+\lambda(4(9-2\beta)a-(16-18\beta+3\beta^2)c+(48+14\beta-5\beta^2)k+(12+2\beta-\beta^2)r)]^2$	$\frac{1}{9(\beta(154-294\lambda-\beta(81-7\beta-25\lambda))+792\lambda-80)^2}[(2(8-\beta)(-2(1-\beta)(-21k-10r+3c(-1+\beta)+33k\beta+17r\beta+3a(-4+7\beta))+(-22(3c+21k+10r)+66a(-4+\beta)+\beta(2r(23+\beta)+3c(-8+3\beta)+3k(16+5\beta)))\lambda)^2)]$

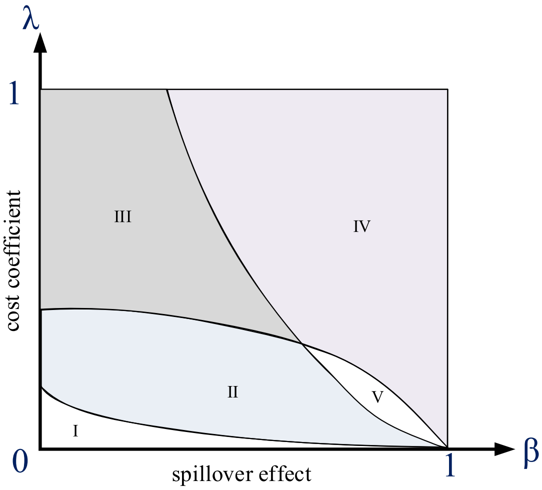

FIGURE 5. Optimality of compatibility and multihoming strategies under different parameters. Note: a = 10, k = 5, r = 5, and c = 3.

understandable that if either the spillover effect is high or the compatibility cost coefficient is high, Firm 1 will not choose the compatibility strategy because the high spillover effect makes Firm 1 lose demand under the W operating system, and the high cost decreases the profit directly. Interestingly, when the compatibility cost and cross effect are both low, multihoming Firm 1 still chooses the incompatibility strategy. Compatibility with the firm under the traditional operating system is a strategy that works, as does cooperation with Firm 2 to ease the competition on the traditional system. However, if the spillover effect and the compatibility cost are both low enough, then the compatibility strategy works similarly to the incompatibility strategy with no cost or spillover effect. Under these conditions, instead of the costly compatibility strategy, competing directly with the firm under the traditional operating system is better. On the other hand, if the spillover effect is low enough, then the multihoming software is more competitive than the mature software under the major/traditional operating system.

The multihoming firms should use their advantage to compete with Firm 2 directly but not adopt the compatibility strategy.

Firm 1 chooses the compatibility strategy in Areas II and III, which Fig. 5 shows. Firm 2 chooses the multihoming strategy in Areas III and IV. In Areas I and V, neither the compatibility nor multihoming strategy is chosen by any firm. If the compatibility cost is not high, competition between Firm 1 and Firm 2 is fierce. Then, Firm 2 cannot enjoy the free ride which comes with the compatibility strategy but instead adopts the multihoming strategy for the emerging operating system.

B. PRICE COMPETITION

Proposition 4: When $\beta \in (0, \beta_0)$, Firm 1 and Firm 2 compete more fiercely with an increasing β, while if $\beta \in (\beta_0, 1)$, the price competition between Firm 1 and Firm 2 decreases with an increasing β, and

$$\beta_0 = \frac{1}{6a + 3\lambda c + (8+5\lambda)k + (4+\lambda)r}\Bigg((4-4\lambda)a + (12\lambda - 1)c + (5+12\lambda)k + 2(1+\lambda)r - \sqrt{\begin{pmatrix} 4a - c + 5k + 2r \\ +2\lambda(-2a + 6c + 6k + r)\end{pmatrix}^2 + 2\begin{pmatrix} 6a + 3\lambda c + (4+\lambda)r \\ +(8+5\lambda)k \end{pmatrix}((1-16\lambda)c - k - 6r\lambda - (1-6\lambda)a)}\Bigg)$$

Proposition 4 shows that when the spillover effect is moderate, the competition between the firm that adopts the compatibility strategy and the firm that adopts the multihoming strategy is the fiercest. When the spillover effect is small, then Firm 1's software is more competitive even if it adopts the compatibility strategy for the traditional operating system. The two software products are not the same, which means that when Firm 1's software is chosen more often by consumers than Firm 2's, price competition is weak. Similarly, when the spillover effect is large, then Firm 2's software under the traditional operating system is the best choice for the users. Although the two programs are different in another way, price competition is also weak. Fig. 6 shows the price competition between Firm1 and Firm 2.

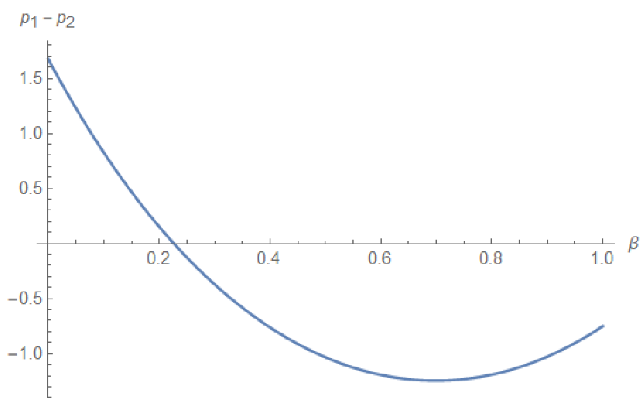

FIGURE 6. Price competition between Firm 1 and Firm 2 Note: a = 10, k = 5, r = 5, and c = 3.

Proposition 5: Firm 1 and Firm 3 compete more fiercely with an increasing β.

Proposition 5 shows the competition between the firm that adopts the compatibility strategy and the firm that assumes the single-homing strategy under the emerging operating system. As the spillover effect increases, more users of Firm 1, which adopted the compatibility strategy, move to Firm 2 under the traditional operating system. Due to the loss of users, Firm 1 must compete with Firm 2 more fiercely to maintain its profit. Similarly, Firm 2 must also compete with Firm 1 based on price to take over the market of the emerging operating system. In the next subsection, we analyze Firm 3's profit under the different equilibrium. Fig. 7 shows the competition between Firm1 and Firm 3.

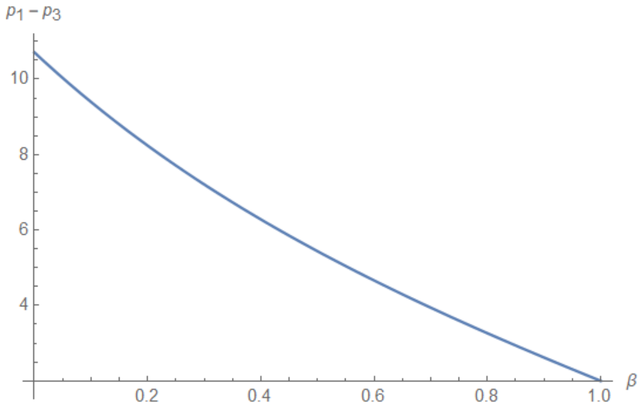

FIGURE 7. Price competition between Firm 1 and Firm 3 Note: a = 10, k = 5, r = 5, and c = 3.

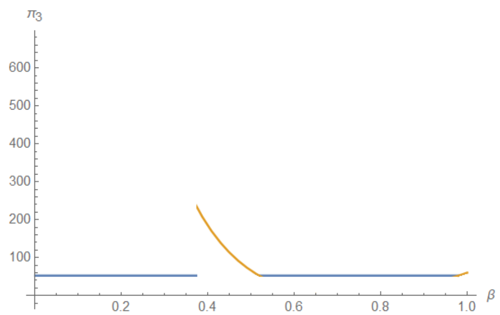

FIGURE 8. Firm 3's optimal profit under different parameters Note: a = 10, k = 5, r = 5, and c = 3.

C. SINGLE-HOMING FIRM PROFIT

In addition to the multihoming and common software, we also analyze the pure single-homing firm's profit. The next proposition summarizes the comparison of the single-homing firm's optimal profit under different scenarios.

Proposition 6: Under the condition of $\lambda \in [0, \lambda(\beta)]$, Firm 3 obtains the optimal profit only when the spillover effect is moderate, where $\lambda(\beta)$ is the solution of $\pi_3^{N*} = \pi_3^{C*}$.

Although Firm 3 faces competition with Firm 1 under the emerging operating system, Firm 3 would not like to face a new competitor and hopes the competition between Firm 1 and Firm 2 is fiercer; therefore, Firm 3 makes the optimal profit. Fig. 6 shows Firm 3's optimal profit.

VI. NUMERICAL VALIDATION

In the previous section, we obtained several analytical results regarding the optimal form of the compatibility and multihoming strategies. In this section, we will briefly report the extensive numerical analysis we conducted. We also verify the theoretical results derived in Section IV. The simulation data used for these numerical computations are assumed to represent real-world conditions as closely as possible. Based on the strategies set, the numerical validation also divides into four cases. We conducted several groups of simulations and chose a set of representative results for this paper: $a = 10$, $k = 5$, $r = 5$, and $c = 3$. We used Wolfram Mathematica 10 to conduct these numerical analyses.

TABLE 4. Firm's profit changes with spillover effect under the incompatibility and single-homing case.

Spillover effect	Firm 1's profit	Firm 2's profit	Firm 3's profit
0.1	182.25	81.28	52.53
0.2	182.25	81.28	52.53
0.3	182.25	81.28	52.53
0.4	182.25	81.28	52.53
0.5	182.25	81.28	52.53
0.6	182.25	81.28	52.53
0.7	182.25	81.28	52.53
0.8	182.25	81.28	52.53
0.9	182.25	81.28	52.53

TABLE 5. Firm's profit changes with compatibility cost under the incompatibility and single-homing case.

Compatibility cost	Firm 1's profit	Firm 2's profit	Firm 3's profit
0.1	182.25	81.28	52.53
0.2	182.25	81.28	52.53
0.3	182.25	81.28	52.53
0.4	182.25	81.28	52.53
0.5	182.25	81.28	52.53
0.6	182.25	81.28	52.53
0.7	182.25	81.28	52.53
0.8	182.25	81.28	52.53
0.9	182.25	81.28	52.53

A. INCOMPATIBILITY & SINGLE-HOMING

Table 4 and 5 show that the firm's profit changes with the spillover effect and compatibility cost in the incompatibility and single-homing case. Since Firm 1's software is not compatible with Firm 2's software, the spillover effect does not work in this case, neither the compatibility cost. The firms' profits only depend on the market potential. The numerical results in Table 4 are consistent with the results in Lemma 2.

TABLE 6. Firm's profit changes with spillover effect under the incompatibility and multihoming case.

Spillover effect	Firm 1's profit	Firm 2's profit	Firm 3's profit
0.1	110.64	110.64	31.41
0.2	110.64	110.64	31.41
0.3	110.64	110.64	31.41
0.4	110.64	110.64	31.41
0.5	110.64	110.64	31.41
0.6	110.64	110.64	31.41
0.7	110.64	110.64	31.41
0.8	110.64	110.64	31.41
0.9	110.64	110.64	31.41

B. INCOMPATIBILITY & MULTIHOMING

Table 6 and 7 show the firm's profit changes with the spillover effect and compatibility cost in the incompatibility and multihoming case. Since Firm 1's software is not compatible with Firm 2's software, the spillover effect does not work in this

TABLE 7. Firm's profit changes with spillover effect under the incompatibility and multihoming case.

Compatibility cost	Firm 1's profit	Firm 2's profit	Firm 3's profit
0.1	110.64	110.64	31.41
0.2	110.64	110.64	31.41
0.3	110.64	110.64	31.41
0.4	110.64	110.64	31.41
0.5	110.64	110.64	31.41
0.6	110.64	110.64	31.41
0.7	110.64	110.64	31.41
0.8	110.64	110.64	31.41
0.9	110.64	110.64	31.41

case, neither the compatibility cost. The firms' profits only depend on the market potential. Comparing Tables 4 and 5, if Firm 1's software is not compatible with Firm 2's software, Firm 1's profit will decrease. The numerical results in Table 4 are consistent with the results in Lemma 2.

TABLE 8. Firm's profit changes with spillover effect under the compatibility and single-homing case.

Spillover effect	Firm 1's profit	Firm 2's profit	Firm 3's profit
0.1	200.85	124.76	0.11
0.2	198.31	134.77	1.67
0.3	195.20	142.55	4.79
0.4	191.74	148.12	9.21
0.5	188.08	151.51	14.79
0.6	184.31	152.75	21.48
0.7	180.49	151.84	29.29
0.8	176.63	148.78	38.28
0.9	172.72	143.55	48.61

TABLE 9. Firm's profit changes with compatibility cost under the compatibility and single-homing case.

Compatibility cost	Firm 1's profit	Firm 2's profit	Firm 3's profit
0.1	189.92	221.32	6.13
0.2	180.24	167.22	26.74
0.3	177.22	151.74	36.24
0.4	175.74	144.43	41.42
0.5	174.87	140.18	44.66
0.6	174.29	137.40	46.87
0.7	173.89	135.44	48.48
0.8	173.58	133.98	49.70
0.9	173.34	132.86	50.65

C. COMPATIBILITY & SINGLE-HOMING

Table 8 and 9 show that the firm's profit changes with the spillover effect and compatibility cost in the compatibility and single-homing case. Since Firm 1's software is compatible with Firm 2's software, the spillover effect works in this case. Firm 1's profit decreases with the increasing spillover effect. Firm 2's profit increases first and then decreases with the increasing spillover effect. Moreover, Firm 3's profit increases with the increasing spillover effect. Comparing Tables 4 and 6, if Firm 1's software is not compatible with Firm 2's software, Firm 1's profit will decrease. The numerical results in Table 8 are consistent with the results in Lemma2 and Proposition 2.

TABLE 10. Firm's profit changes with spillover effect under the compatibility and multihoming case.

Spillover effect	Firm 1's profit	Firm 2's profit	Firm 3's profit
0.1	138.24	129.18	0.16
0.2	134.23	136.40	0.33
0.3	130.43	142.24	2.12
0.4	126.92	146.78	5.11
0.5	123.72	150.05	9.06
0.6	120.84	152.08	13.80
0.7	118.29	152.82	19.27
0.8	116.07	152.24	25.45
0.9	114.169	150.22	32.39

TABLE 11. Firm's profit changes with compatibility cost under the compatibility and multihoming case.

Compatibility cost	Firm 1's profit	Firm 2's profit	Firm 3's profit
0.1	126.43	190.25	4.67
0.2	118.86	162.18	18.14
0.3	116.52	153.85	24.16
0.4	115.39	149.86	27.42
0.5	114.72	147.52	29.45
0.6	114.27	145.98	30.83
0.7	113.96	144.89	31.84
0.8	113.72	144.07	32.60
0.9	113.54	143.45	33.19

D. COMPATIBILITY & MULTIHOMING

Table 10 and 11 shows that the firm's profit changes with the spillover effect and compatibility cost in the compatibility and multihoming case. Since Firm 1's software is compatible with Firm 2's software, the spillover effect works in this case. Firm 1's profit decreases with the increasing spillover effect. Firm 2's profit increases first and then decreases with the increasing spillover effect. Moreover, Firm 3's profit increases with the increasing spillover effect. The numerical results in Table 10 are consistent with the results in Lemma2 and Proposition 2.

VII. CONCLUSION

Building on the context of the multihoming software economy, we develop a competition model to study a software firm's optimal compatibility strategy with a single-homing firm's competition under the emerging operating system. We incorporate into the model the distinct features of this context: the multihoming software's compatibility level, the spillover effect of the traditional operating system, and the mature software firm's free ride from the compatibility strategy. In this work, we characterize multihoming software strategic decisions regarding the spillover effect and compatibility cost. We examine the implications of the spillover effect for the multihoming firm, the mature firm, and the single-homing firm under the emerging operating system.

Whether the multihoming software firm makes a compatibility decision is determined by the tradeoff between the spillover effect and the compatibility cost. When the spillover effect is not high and the compatibility cost is moderate, multihoming firm should adopt the compatibility decision. Additionally, the compatibility level is positively correlated with the software price no matter whether the mature software firm under the traditional operating system adopts the multihoming strategy. Interestingly, when the spillover effect and the compatibility cost are both low enough, the multihoming firm should not adopt the compatibility strategy because the compatibility level is too low to attract consumers into the emerging operating system market, and the multihoming firm cannot make a profit. The mature firm is not wise to always enjoy the free ride from the compatibility strategy under the traditional operating system, even if the spillover effect is high. Occasionally, the mature firm choosing the multihoming strategy to compete on the emerging operating system makes a profit when the compatibility cost is high enough.

With IT development and system upgrading, our findings provide the following managerial insights regarding economic and software utilization improvement via operation management decisions, especially for those software firms that have just entered a new market and are reconsideringtheir compatibility decisions, such as the E-learning program on the iPad [32]. We suggest that managers consider the following. First, new multihoming firms compete with traditional firms. Our study highlights the nuanced but important difference between the software development economy and the traditional economy. Given that multihoming software is always developed with the emerging operating system, it is imperative for firms and users to understand the market, especially given the complexities associated with the competitive environment and compatibility strategy that firms employ. Second, a compatibility strategy in the software development economy is still important. Critics argue that compatibility may limit the core vision of creativity; multihoming firms must act as developers; only by taking innovation as their first priority can they guarantee dominance in emerging systems. Our analysis provides the analytical backbone of this debate. Moreover, a compatibility strategy works as a cooperation strategy to ease competition with the mature firms, saving the multihoming firms' energy on the traditional operating system but focusing on the emerging operating system.

Some important extensions to this paper can be considered in future research. First, we use a stylized model that abstracts away many operational details, such as any quality preference of heterogeneous consumers and multiple time periods. Adding these factors would lead to a richer model and possibly provide additional insights. Second, this paper assumes that the multihoming firm's software is compatible with only one single-homing firm. Another possible direction for future research is to consider that multihoming firms' software is compatible with more single-homing firms supporting different operating systems.

APPENDIX PROOFS

A. PROOF FOR LEMMA 1

The first-order derivatives of the profit function (44) are:

$$\begin{aligned} \partial\pi_1/\partial p_1 &= a + 2c + 2k + r + l - 4p_1 + (-4+\beta)\,p_1 \\ &\quad +2p_2 + 2p_3 - \beta\,(c + k + l - p_1 + p_3)\,, \qquad (46) \\ \partial\pi_1/\partial l &= -\lambda l + (1-\beta)\,p_1. \qquad (47) \end{aligned}$$

Similarly, we get the second order derivatives,

$$\partial^2\pi_1/\partial p_1^2 = 2\beta - 8, \quad \partial^2\pi_1/\partial p_1\partial l = 1-\beta, \quad \partial^2\pi_1/\partial l^2 = -\lambda.$$

Then, the Hessian matrix of the profit function is:

$$\begin{bmatrix} -8+2\beta & 1-\beta \\ 1-\beta & -\lambda \end{bmatrix}$$

To ensure that the sequential principal minors are negatively definitive, the Hessian determinant must meet the following conditions:

$H_1 = -8 + 2\beta < 0$ and $H_2 = \lambda(8-2\beta) - (1-\beta)^2 > 0$

Therefore, we get the condition $\lambda(8-2\beta) - (1-\beta)^2 > 0$.

$$\begin{cases} p_1 = \dfrac{(-4\,(3a+2c+6k+3r) + (3c+5k+r)\,\beta)\,\lambda}{4 - 48\lambda + \beta\,(-7+3\beta+10\lambda)} \\ p_2 = \dfrac{2\,(-1+\beta)\begin{pmatrix} c-k \\ +4k\beta+2r\beta \\ +a\,(-1+3\beta)\end{pmatrix} + \begin{pmatrix} 16c - 12\,(4k+r) \\ -2\,(9c+7k+r)\,\beta \\ +(3c+5k+r)\,\beta^2 \\ +4a\,(-9+2\beta)\end{pmatrix}\lambda}{8 - 96\lambda + 2\beta\,(-7+3\beta+10\lambda)} \\ p_3 = -\dfrac{(-1+\beta)\begin{pmatrix} 3a+c+7k \\ +4r-(2k+r)\,\beta\end{pmatrix} + \begin{pmatrix} 6a + k\,(24-5\beta) \\ +c\,(-8+\beta) \\ -3r\,(-6+\beta)\end{pmatrix}\lambda}{4 - 48\lambda + \beta\,(-7+3\beta+10\lambda)} \\ l = \dfrac{(-1+\beta)\,(12a+8c+12\,(2k+r) - (3c+5k+r)\,\beta)}{4 - 48\lambda + \beta\,(-7+3\beta+10\lambda)} \end{cases} \qquad (51)$$

B. PROOF FOR LEMMA 2

Take the compatibility and single-homing case as an example, the other cases' proof is same.

Under the condition in Lemma 1, the first-order derivatives of the profit function (45) are:

$$\partial\pi_2/\partial p_2 = a - c + k + 2p_1 - 4p_2 + \beta\left(c + k + \alpha - p_1 + p_3\right) \tag{48}$$

$$\partial\pi_3/\partial p_3 = -c + k + r - \alpha + 2p_1 - 4p_3 \tag{49}$$

Let the first-order derivatives of (44) and (45) be equal to 0, we get

$$\begin{cases} a + 2c + 2k + r + l - 4p_1 + (-4+\beta)\,p_1 \\ +2p_2 + 2p_3 - \beta\left(c + k + l - p_1 + p_3\right) = 0 \\ -\lambda l + (1-\beta)\,p_1 = 0 \\ a - c + k + 2p_1 - 4p_2 + \beta\left(c + k + \alpha - p_1 + p_3\right) = 0 \\ -c + k + r - \alpha + 2p_1 - 4p_3 = 0 \end{cases} \tag{50}$$

Solving the above equations, we obtain the optimal solutions as, (51) shown at the bottom of the previous page. Take the optimal solutions back to the profit function (44) and (45), we obtain the optimal profit under the compatibility and single-homing case.

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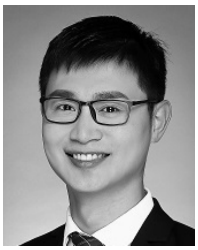

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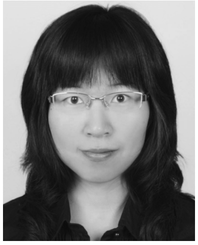

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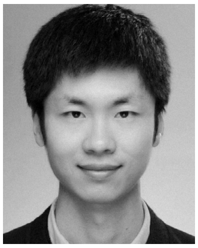

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