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CAN FIRMS IMPROVE PERFORMANCE THROUGH EXTERNAL CONTRIBUTIONS TO THEIR OPEN-SOURCE SOFTWARE PROJECTS?

Jin Hu
The University of Hong Kong, jinhu@connect.hku.hk

Daning Hu
Southern University of Science and Technology, hdaning@gmail.com

Xuan Yang
University of Zurich, xuanyang06@gmail.com

Michael Chau
The University of Hong Kong, mchau@business.hku.hk

CAN FIRMS IMPROVE PERFORMANCE THROUGH EXTERNAL CONTRIBUTIONS TO THEIR OPEN-SOURCE SOFTWARE PROJECTS?

Research in Progress

Jin Hu, The University of Hong Kong, Hong Kong, and Southern University of Science and Technology, Shenzhen, China, jinhu@connect.hku.hk

Daning Hu, Southern University of Science and Technology, Shenzhen, China, hdaning@gmail.com

Xuan Yang, University of Zurich, Zurich, Switzerland, xuanyang06@gmail.com

Michael Chau, The University of Hong Kong, Hong Kong, mchau@business.hku.hk

Abstract

A growing number of firms are developing open-source software (OSS) projects to get external contributions from developers unaffiliated with them. We investigate the impact of external contributions to a firm's OSS projects on its performance measured by Tobin's q and how the amount of comment activities within the firm's OSS projects moderates this effect. Using a panel of 536 publicly listed firms over 2011-2019, we find that external contributions to a firm's OSS projects have a positive impact on the Tobin's q value of the firm. Moreover, this performance effect is strengthened when there are more comment activities within the firm's OSS projects. Our study contributes to the literature and generates managerial implications for firms and OSS communities.

Keywords: External contributions, Open-source software, Firm performance, Comment activity.

1 Introduction

As the business world becomes increasingly technology-focused and open collaborative innovation strategies become popular, a growing number of firms, including over 90% of Fortune 100 companies, are engaging with the open-source software (OSS) community (Daniel et al., 2018; Chen et al., 2022a),. These firms use major OSS community platforms like GitHub to create and manage firm-hosted OSS projects (Chen et al., 2022a), which source external resources like code contributions from developers outside their organizations (i.e., external contributions), aiming to capture business value and achieve innovation (Chengalur-Smith et al., 2010; Conti et al., 2021). Although it was suggested that such external contributions can bring novel and independent insights to firm-hosted OSS projects (Lin and Maruping, 2021; Setia et al., 2012), their impact on a firm's market-based business performance is largely unknown. As Bonaccorsi and Rossi (2006) suggested that one of firms' incentives to engage in OSS activities is to seek profit, providing empirical evidence that external contributions improve firms' performance can significantly influence managerial decisions to adopt this novel and open software production model. This not only positively affects firms' interests but also can contribute more public goods to the OSS community in general.

However, existing studies mainly focused on the impact of external contributions on firms' venture capital investment (Yang, 2019) and reputation (Garomssa et al., 2022; Sims, 2013). Few have delved into firms' business performance based on financial data, such as Tobin's q. In addition, these few studies were confined to small and young firms that often have costly internal research and development (R&D) activities (Ortega-Argilés et al., 2009) and may benefit more from external contributions. It is unclear whether and how external contributions can improve the Tobin's q value of public listed firms

that are often more mature and established. As one of firms' main goals is to achieve desirable business performance (Kallunki et al., 2011), it is crucial to understand the impact of external contributions on firms' Tobin's q and the conditions under which such performance effect can be strengthened. As such, this study investigates the following research questions: (1) Do external contributions to firm-hosted OSS projects positively affect firm performance measured by Tobin's q? And if yes, (2) What factors may moderate such positive effect?

We compile a unique dataset that contains firm-quarter-level OSS activities and financial statements from 2011 to 2019. Our final sample includes 536 North American publicly listed firms with GitHub accounts. Using an instrumental variable (IV) approach, we find that external OSS contributions significantly improve firms' Tobin's q values. We also find that this positive performance effect is strengthened when there is more comment activity within the firm's OSS projects.

Our contributions to the literature are as follows. First, to the best of our knowledge, our study is among the first to empirically study the impact of external OSS contributions on the performance of publicly listed firms. Our results not only provide an explanation as to why many firms are hosting OSS projects but also highlight the growing importance of IT intangibles such as OSS contributions for firms. Second, this study advances our understanding of the mechanisms under which the performance effect of external OSS contributions is strengthened by comment activity within the firm's OSS projects. Third, from the methodology perspective, our study is one of the earliest attempts aiming to study the causal effect of external OSS contributions on firm performance using an IV approach. Different from previous studies focusing on statistical correlations which might be contaminated by confounders (Sims, 2013; Garomssa et al., 2022), IV can alleviate the potential endogeneity bias due to unobserved confounding, which leads to a clearer identification of the causal impact of external OSS contributions on firm performance.

Our study also provides managerial implications for firms and OSS communities. First, our results shed light on the significant economic benefits accrued from external OSS contributions, which can significantly affect firms' strategic decisions on adopting the OSS production model to enhance their competitive advantage and performance. Second, our findings suggest that firms promote comment interactions within their OSS projects to capture and transform more values. Third, our study provides OSS communities with valuable insights into achieving win-win cooperation with firms as these communities can leverage the reputation of their firm users to attract more developers and contributions.

2 Literature Review

While engaging with the OSS community is generally considered as a risky endeavor for firms (Singh, 2020), it can also offer benefits for firms (Lerner et al., 2006; Spaeth et al., 2010). Firms typically engage with the OSS community in three ways: (1) using OSS, (2) internal developer participation, and (3) hosting and developing OSS projects that enable firms to acquire external OSS contributions. We then discuss the negative and positive effects of such engagements on firm performance found in previous research as follows. For the first way, firms utilizing OSS may encounter technical challenges due to the absence of guaranteed centralized technical support as found in proprietary software. Instead, OSS primarily relies on voluntary contributions from a geographically dispersed community of developers (Nagle, 2019; Woods, 2005). Kogut and Metiu (2001) note that, despite continuous maintenance by OSS developers, there is often no guarantee of future versions of an OSS project. Furthermore, the lack of a contractual relationship between firms using OSS and contributing developers may expose the firms to security risks and liability (Nagle, 2019). Conversely, there is a stream of literature that discussed the benefits of OSS usage for firms and empirically examined its impact on firm performance. By using free OSS, firms can reduce software development costs (Samuelson, 2006) and circumvent expensive licensing fees imposed by proprietary software providers (Bonaccorsi et al., 2006). For small startups, the use of the OSS code drastically reduces the need for costly internal R&D (Gruber and Henkel, 2006). Firms can also identify pools of knowledge useful for their internal innovation processes by using OSS (Spaeth et al., 2010). In addition to these conceptual benefits, OSS usage has also been empirically shown to improve firm performance. For example, Harison and Koski (2008) survey 591 Finnish software firms and discover that using OSS substantially reduces labor input in developing new software

products, thereby increasing value added per employee. Likewise, Nagle (2019) finds that using OSS significantly enhances value-added returns for firms within an ecosystem of complements.

The second way involves fostering internal developer participation. Many firms encourage their internal developers to contribute to the OSS community. At first glance, this may appear to be unprofitable, as firms seemingly sacrifice their own workforce to assist others. Moreover, allocating time and personnel to establish and maintain connections with the OSS community may divert firms from managing their core business activities, leading to project coordination, communication, and other transaction costs (O'Mahony and Bechky, 2008; Stam, 2009). We summarize the reasons for this ostensibly unprofitable behavior from prior literature as follows. First, internal developers can learn and improve skills by contributing to OSS development. When collaborating with fellow OSS contributors to evaluate code submissions and fix bugs, internal developers can improve their programming skills and get familiar with the OSS they contributed to, which allows the firm to better utilize that software (Lerner et al., 2006; Nagle, 2018). Second, firms may identify potential employees from the OSS community. Previous literature has suggested that internal developers could discover potential hires when collaborating with OSS community members (Lerner et al., 2006; Lerner and Tirole, 2002). Third, firms can enhance their reputation by fostering their internal developers to contribute to the OSS community. This positive reputation helps firms save marketing costs and attract capital investments (Lerner et al., 2006).

Several empirical studies have examined the impact of internal developers' OSS contributions on firm performance, with a majority supporting a positive performance effect. Stam (2009) surveys 90 Dutch firms and finds an inverted U-shaped relationship between internal developers' contributions to the OSS community and the firm performance they perceive. Nagle (2018) identifies firms with internal developers who contributed to Linux Foundation and observes that these firms obtain twice the productive value from using Linux compared to their free-riding peers. Yu (2020) analyzes survey data and finds a positive effect of internal developers' OSS contributions on perceived firm performance.

The third way for firms to engage with the OSS community is by hosting and developing OSS projects. Firms developing OSS projects may inadvertently provide strategic resources to their competitors, thereby relinquishing control over proprietary knowledge (Henkel, 2006). Moreover, the strong embeddedness of firms in the OSS community may result in redundant information, causing firms to allocate additional time and resources to sort and filter information (Uzzi, 1997). Conversely, hosting and developing OSS projects also yields benefits for firms, including acquiring external OSS contributions, enhancing reputation, expanding customer bases, and selling complementarities and services (Singh, 2020; Yang, 2019). Existing empirical studies suggest an overall positive performance effect from firms developing OSS projects. Startups that develop OSS projects on GitHub are also more likely to secure a financing round (Conti et al., 2021). Recent empirical research further demonstrates that developing more OSS projects leads to improved financial performance for publicly listed firms (Aksoy-Yurdagul, 2015; Singh, 2020) and increased valuation for startups (Lin and Maruping, 2021).

The most notable advantage for firms that develop OSS projects is the free access to extensive external OSS contributions (Yang, 2019). These contributions are crucial to the growth of a firm's OSS projects, as external developers often examine codes from a distinct perspective from that of internal developers, yielding unique and novel insights (Lin and Maruping, 2021). However, only a limited number of studies have investigated the direct performance effect of external OSS contributions. Sims (2013) surveys 250 firms that develop OSS projects in the Drupal community and discovers a positive relationship between the extent to which a firm incorporates ideas and assistance from the community and its software creation productivity. Based on a survey of 200 employees from 60 commercial OSS companies, Garomssa et al. (2022) show a positive correlation between external OSS contributions and employee perceptions of firm success. In contrast to the aforementioned research that relies on survey data, Yang (2019) utilizes secondary data to examine the impact of external OSS contributions on venture capital investment. This study finds that for new ventures that develop OSS projects on GitHub, external contributions to their projects positively influence the amount of venture capital investment they receive.

To summarize, the literature review identifies several research gaps. First, existing literature on OSS and firm performance mainly comprises conceptual work that discusses the costs or benefits firms obtain

by engaging with the OSS community. Empirical research on the impact of firms' engagement with the OSS community on firm performance is still in its infancy, especially research focusing on external OSS contributions. Second, most empirical research relies on survey analysis and focuses on perceived firm performance (Sims, 2013; Garomssa et al., 2022). Only a handful of empirical studies examine actual market-based outcomes (Aksoy-Yurdagul, 2015; Singh, 2020). Moreover, these studies mainly investigate the overall effect of developing OSS projects on firm performance, without emphasizing external OSS contributions. Although Yang (2019) explores the performance effect of external OSS contributions, this study only considers the effect on venture capital investment. As a result, it is crucial to examine the impact of external OSS contributions on firm business performance, such as Tobin's q values, to assess their forward-looking economic value more accurately (Chen et al., 2022b). Third, empirical research focusing on the performance effect of external OSS contributions is limited to small and young firms (Garomssa et al., 2022; Yang, 2019; Sims, 2013). There is a lack of research providing empirical evidence on publicly listed firms that are more mature and established. Finally, it would be valuable to investigate whether contingency factors, such as comment activity within a firm's OSS projects, can moderate the impact of external OSS contributions on firm performance, an area that has been less studied in previous literature.

3 Hypotheses Development

In addition to the challenges of engaging with OSS discussed in Section 2, firms may face additional costs from obtaining and using external OSS contributions. For instance, firms may need to allocate resources to integrate external OSS contributions with their existing software or systems. This can involve additional time, effort, and financial investment to ensure compatibility and seamless integration (Dahlander and Magnusson, 2008). Moreover, as there may be potential risks concerning the quality and reliability of external contributions, firms need to invest in quality assurance processes to verify the suitability and stability of the external OSS contributions, which can increase their operational costs (Mockus et al., 2002). However, our study proposes that external OSS contributions can generate more benefits from external OSS contributions, resulting in a net positive impact on firm performance.

First, external OSS contributions promote the firm's technological advancements and innovations by transferring knowledge from external expertise to the firm. The open and crowdsourced nature of OSS allows firms to access expertise beyond firm boundaries (Nagle, 2019). External contributors help improve the quality of firms' OSS projects by fixing bugs and adding new code. As external developers often contribute to firms' OSS projects to meet their own use needs (Bagozzi and Dholakia, 2006; Shah, 2006), firms gain insights into user needs through these external contributions (Chengalur-Smith et al., 2010; Dahlander and Wallin, 2006), making the firms more competitive in the market. Moreover, unlike internal developers who sometimes fixate on their initial design, external developers usually view code through a different lens, not confined to the current design. Such exposure to diverse perspectives and expertise can drive innovation and enhance the firm's competitiveness in the market (Setia et al., 2012). We suggest that this outweighs the potential risk of competitors utilizing the same open-source code.

Second, firms with external OSS contributions can capture value from the reinforced user base. Firms that develop OSS projects require a broad and loyal user base willing to pay for their priced complementarities or services. OSS literature has observed that most of the crowd contributors are also users of the OSS (Bagozzi and Dholakia, 2006; Shah, 2006). External contributors are inclined to become loyal users of the firm's OSS, as they modify it to better suit their own needs (Yang, 2019). Meanwhile, their familiarity with the firm's OSS increases the switching costs to competing OSS products, strengthening the firm's user base (Yang, 2019). The loyalty and enhanced user base ultimately create a competitive advantage for the firm to compensate for this risk.

Third, firms save costs by acquiring free external OSS contributions. Firms can reduce development costs as external developers voluntarily improve the firms' OSS projects without monetary compensation (Yang, 2019). Moreover, firms can save on labor costs by reallocating their internal developers to other tasks. Compared with the proprietary software development approach within firms, the OSS development model facilitates a more efficient allocation of tasks and resource utilization, while

also reducing managerial labor and auditing expenses (Harison and Koski, 2008). Furthermore, OSS host firms can save on storage costs, as the OSS community maintains code at no charge (Andersen-Gott et al., 2012). These cost savings for firms can offset potential intellectual property risks.

To sum it up, external OSS contributions can promote a firm's technological advancements and innovations, help it capture value from a reinforced user base, and save its costs related to software development. These benefits effectively counterbalance the potential costs, offering firms a net positive impact on their performance. Therefore, we propose the following hypothesis:

H1. *External OSS contributions have a positive effect on firm performance.*

Moreover, comment activities play a crucial role in OSS development, our study further examines whether the amount of comment activities within a firm's OSS projects moderates the effect of external OSS contributions on firm performance. We posit that comment activities within a firm's OSS projects can strengthen the performance effect of external OSS contributions because of the following reasons.

First, comment activities enable contributors to become more attuned to user needs and project goals (Kalliamvakou et al., 2015). Some OSS users, especially those with limited programming skills, may express their requirements through comments. By addressing these comments, external contributors can create new features that not only fulfill their own needs but also cater to other users' demands, thus reinforcing the firm's user base. Moreover, external developers, especially newcomers, can gain a better understanding of project goals through comment interactions with incumbent project members, enabling them to better align their contributions with the firm's requirements and enhance their contributions' effectiveness. Active commenting can also foster a welcoming and inclusive atmosphere for newcomers, promoting their continued contributions (Daniel and Stewart, 2016; Howison and Crowston, 2014).

Second, comment activities within the firm's OSS projects also facilitate cooperation and knowledge integration among the contributors, which are crucial for OSS development (Tiwana and Keil, 2007). However, OSS developers may possess different perspectives and thought processes, which can complicate collaboration. Moreover, some OSS developers might become fixated on their design and resist changes proposed by others due to interpretive barriers and lack of trust (Setia et al., 2012). Trust is essential for cooperation, especially in virtual settings (Paul and McDaniel, 2004). Tensions among contributors can impede teamwork and diminish the quality of their contributions to the firm's OSS. As contributions increase, so does the need for comment activity. For example, an array of external OSS contributions may encompass numerous potentially viable features, but some might conflict with one another, necessitating contributors to prioritize these additions through comments (Daniel and Stewart, 2016). Contributors can use the comments section to discuss whether and when to add functions. Moreover, promoting comment activity within the firm's OSS projects helps contributors in overcoming interpretive barriers (Daniel and Stewart, 2016) and fostering trust and cohesion (Dahlander and Wallin, 2006). Consequently, the contributors can work more efficiently and effectively with each other. Enhanced cooperation and knowledge integration among contributors allows external OSS contributions to be better assimilated into the entire project and utilized more effectively. Overall, we hypothesize:

H2. *The positive effect of external OSS contributions on firm performance is strengthened when there are more comment activities within the firm's OSS projects.*

4 Data

Our dataset comes from two sources: Compustat (North America) and GitHub. Compustat (North America) contains financial data of publicly listed firms in North America. GitHub is the largest OSS community in the world. We acquire GitHub data by crawling through its API and searching on GH Archive, which archives the public GitHub timeline.

We first downloaded the fundamental information (e.g., company name and web URL) of all the 13,817 North American firms available on Compustat. At the same time, we crawled the profiles (e.g., login, name, company, blog, and email) of all the 975,848 organizational users on GitHub. To identify the GitHub accounts of each firm, we (1) matched the company name from Compustat with the login, name, and company from GitHub, and (2) matched the domain of web URL from Compustat with the domain

of email and blog from GitHub. Our matching algorithm requires that both fields contain at least one identical string after deleting the stop words and other common strings (e.g., "http", "www", and "com"). For example, if the web URL of firm A in Compustat is "www.A.com", and the email domain of organization B in GitHub is "@B.A.com", firm A and organization B are matched because both fields contain the same string "A". After matching, we manually selected the exactly matched firm-organizations in various ways, such as comparing the logo on the firm's website with the organization's avatar on GitHub. Finally, we identified 816 publicly listed firms that have GitHub accounts. Since some firms have missing financial data in Compustat, we excluded observations with missing data on any of the financial-related variables in our empirical models, which leads to a final sample of 8,756 firm-quarter observations with 536 unique firms from the first quarter in 2011 to the last quarter in 2019.

5 Empirical Analysis

We use the following specification to test H1:

$$TobinQ_{it} = \beta_0 + \beta_1 ExternalContributions_{it} + \eta' X_{it} + \delta_i + \theta_t + \varepsilon_{it} \quad (1)$$

where i indexes the firms and t indexes the quarters. The dependent variable, *TobinQ*, is calculated as the firm's market value over the replacement value of its assets (Tobin, 1969). Tobin's q is a commonly used market-based measure of firm performance (Bharadwaj et al., 1999; Chung et al., 2020) and has the ability to address the limitations of accounting measures due to its forward-looking and risk-adjusted nature (Chen and Lee, 1995). *ExternalContributions* is the external OSS contributions, which is measured by the number of commits from the firm's external contributors to its OSS projects (Chen et al., 2022a). We use four approaches to distinguish between internal and external contributors of the firm. First, some firms disclosed the list of affiliated members in GitHub. Second, we checked whether the company that the contributor reports in her profile is the focal sample firm. Third, we compared each contributor's email/blog domain with the firm's website domain to see if they are the same. Fourth, we identified contributors who have the right to modify the firm's OSS projects directly. Since these approaches are conservative in identifying internal contributors, we consider a contributor as internal if at least one approach indicates so. We consider all other contributors of the firm as external contributors and their contributions as external contributions (Chen et al., 2022a). We then aggregate all commits contributed by the external contributors to the firm level for each target firm in each quarter and measure *ExternalContributions*. X_{it} is the vector of control variables, which include the number of commits from the firm's internal contributors to its OSS projects (*InternalContributions*), the number of quarters since the firm created a GitHub account (*GitHubAge*), the total number of OSS projects developed by the firm (*Projects*), the number of stars received by the firm's OSS projects (*Stars*), and the number of issue reports received by the firm's OSS projects (*Issues*), total assets (*Assets*), R&D intensity (*RDIntensity*), leverage (*Leverage*), sales growth (*SalesGrowth*), and selling, general, and administrative (SGA) intensity (*SGAIntensity*). δ_i is the firm fixed effect. θ_t is the quarter fixed effect. ε_{it} is the error term.

To test H2, we estimate the following specification:

$$TobinQ_{it} = \beta_0 + \beta_1 ExternalContributions_{it} + \beta_2 ExternalContributions_{it} \times Comments_{it} + \beta_3 Comments_{it} + \eta' X_{it} + \delta_i + \theta_t + \varepsilon_{it} \quad (2)$$

where *Comments* represents comment activities within the firm's OSS projects, which is measured by the number of comments within the firm's projects. Following Chen et al., (2019), we take the natural logarithm of all variables in Equations (1) and (2) to control for their skewness and the different absolute frequency. To handle zero values of the raw variables, we added one to them before taking the logarithms.

In our empirical models, there is possible endogeneity of *ExternalContributions*. The first concern is reverse causality. For example, firms with good performance are more likely to attract external developers who admire them and thus contribute more to their OSS projects. Second, even though the firm fixed effects capture the firm-level time-invariant characteristics in the models, there might exist unobserved time-variant factors that influence both external contributions and Tobin's q. Therefore, we consider an IV for *ExternalContributions* (*ExternalContributionsIV*) as follows to address the potential endogeneity concerns: We first identify the external contributors of a firm in one quarter. Then, we

count the number of commits these external contributors contributed on GitHub in that quarter, but to OSS projects that do not belong to the focal firm or its peers. We consider peer firms as those that operate in the same two-digit North American Industry Classification System code as the focal firm.

ExternalContributionsIV satisfies the relevance and exclusion restriction criteria of a valid IV. First, since *ExternalContributionsIV* and *ExternalContributions* both represent the degree to which the external contributors contribute to OSS projects on GitHub, there should be a positive relationship between the two variables. We estimate the first-stage regression by regressing *ExternalContributions* on *ExternalContributionsIV* (along with all control variables). The results show that the coefficient of *ExternalContributionsIV* is significant and positive ($\beta = 0.431, p < 0.01$), which verifies the IV's relevance. Moreover, the F statistic for the IV is 148.49, which crosses the weak instrument threshold of 10 calculated by Stock and Yogo (2002). Therefore, *ExternalContributionsIV* is a strong IV. Second, *ExternalContributionsIV* is unlikely to be directly correlated with Tobin's q because a firm's performance is unlikely to be affected by contributions to OSS projects that are neither its own nor its peers'. It is thus reasonable to assume that *ExternalContributionsIV* satisfies the exclusion restriction.

	Dependent variable: *TobinQ*	
	(1)	**(2)**
ExternalContributions	0.106***	0.106***
	(0.019)	(0.019)
ExternalContributions × *Comment*		0.003***
		(0.001)
Comment		-0.017**
		(0.007)
InternalContributions	-0.035***	-0.034***
	(0.006)	(0.006)
GitHubAge	-0.064***	-0.064***
	(0.010)	(0.010)
Projects	0.054***	0.050***
	(0.011)	(0.011)
Stars	0.000	-0.001
	(0.005)	(0.005)
Issues	-0.008	-0.012
	(0.006)	(0.007)
Assets	-0.244***	-0.244***
	(0.013)	(0.013)
RDIntensity	-0.466	-0.458
	(0.315)	(0.318)
Leverage	0.031	0.030
	(0.038)	(0.038)
SalesGrowth	0.008	0.009
	(0.012)	(0.012)
SGAIntensity	1.996***	1.999***
	(0.186)	(0.188)
Constant	2.289***	2.293***
	(0.115)	(0.116)
Firm fixed effects	Yes	Yes
Quarter fixed effects	Yes	Yes
Number of observations	8,756	8,756

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$. Standard errors are in parentheses. All variables are in a natural logarithm form.

Table 1. Results.

Table 1 shows the IV regression results of Equations (1) and (2) in Columns (1) and (2), respectively. The coefficient of *ExternalContributions* in Column (1) is positive and significant ($\beta = 0.106, p < 0.01$), suggesting that external OSS contributions have a positive effect on firm performance measured by Tobin's q. Therefore, H1 is supported. In Column (2), while the coefficient of *ExternalContributions* is still positive and significant, the coefficient of *ExternalContributions* × *Comments* is positive and

significant ($\beta = 0.003, p < 0.01$), suggesting that external OSS contributions further improve firm performance when there are more comment activities within the firm's OSS projects. So H2 is supported. A possible explanation for the significantly negative coefficient of *Comments* is that more comments may reflect more unsolved needs or problems within the firm's projects.

6 Conclusion and Future Research

The OSS community is thriving, attracting significant industrial and academic interest in its potential for generating business value. By examining the impact of external OSS contributions on the Tobin's q value of publicly listed firms, our study offers several contributions. First, our study expands existing work by advancing research in the relationship between OSS and firm business value. While current research primarily focuses on theoretical discussions surrounding whether firms should engage with the OSS community (Lerner et al., 2006; Shaikh and Levina, 2019; Spaeth et al., 2010), there is a scarcity of empirical research examining the performance effects of such engagement, particularly regarding external OSS contributions. Recent studies have called for more empirical investigation into the performance implications of firms' engagement with the OSS community (Nagle, 2019; Singh, 2020).

Moreover, though external contributions to firm-hosted OSS have been shown to increase investment received by firms (Yang, 2019) and employee perception of firms (Garomssa et al., 2022; Sims, 2013), these studies are limited to small and young firms and do not measure firm performance using financial data. Our study extends this line of inquiry by empirically investigating the effect of external OSS contributions on the performance of publicly listed firms, specifically in terms of their Tobin's q values. We find that external OSS contributions significantly and positively affect a firm's Tobin's q and this effect is amplified when there are increased comment activities within the firm's OSS projects.

Lastly, our study also offers valuable managerial insights for firms and OSS communities. By highlighting the considerable economic benefits derived from external contributions to firm-hosted OSS, our study can help firm managers make informed decisions in hosting OSS projects. We encourage firm stakeholders to appreciate the value of external OSS inputs and consider attracting external contributions to their OSS projects as a strategic action to enhance their competitive advantage and performance, particularly for those who may be hesitant about the economic value of the external OSS contributions.

In future research, we plan to examine additional moderating factors, such as the project similarity between a firm and its external contributors, and their influence on the impact of external OSS contributions on Tobin's q. On one hand, when a firm and its external contributors have similar OSS projects, the firm may easily absorb and effectively leverage the external OSS contributions (Chen et al., 2022a; Daniel et al., 2018). On the other hand, such knowledge redundancy could reduce opportunities for innovations and market exploration (Makri et al., 2010). Building on Chen et al. (2022a), we plan to use project descriptions from GitHub to measure project similarity between a firm and its external contributors. We will first vectorize the project descriptions using the term frequency-inverse document frequency (TF-IDF) scores, then calculate the cosine similarity between all pairs of vectors from the firm's projects and its external contributors'. Subsequently, we will aggregate the scores to capture the overall project similarity between the target firm and its external contributors. Moreover, we will test the robustness of our results by employing alternative measurements and econometric specifications, as well as constructing more valid instrumental variables. Additionally, we will examine the heterogeneous effects within our findings.

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