Do user innovation and producer innovation act as complements or as substitutes in the market for product add-ons?: The case of downstream co-creation in video games

Jing Tang
The Ohio State University
tang.1489@buckeyemail.osu.edu

Richard Makadok
The Ohio State University
makadok.2@osu.edu

April 2025

Abstract:

Users have long been recognized as valuable sources of innovation that can complement producer-driven development. However, significant ambiguity persists regarding the relationship between producer and user innovation—specifically whether they function as substitutes or complements. A critical conceptual gap impeding progress in this research stream is the failure to distinguish between two distinct innovation domains: the development of entirely new products versus the modification of existing ones. This study leverages a unique platform dataset that provides an unprecedented "level playing field" for measuring product modifications made to identical focal products by both users and producers, but where each producer has been given the option to give its users a platform through which they can share their user innovations with other users. We conduct two interrelated empirical investigations: First, we examine the cross-sectional relationship between producers' adoption of user-modification-supporting policies (i.e., implementing a platform for users to share their innovations) and their implementation of producer-modification-supporting policies. Second, we analyze the dynamic temporal relationship between the volume of user modifications and producer modifications as they accumulate over time among producers who have adopted both policy types (i.e., supporting the implementation of both producer innovation and user innovation). Our findings reveal a notable asymmetry: the relationship between policies supporting these two innovation sources differs significantly from the relationship between the actual volumes of innovations generated from each source. This distinction offers important theoretical insights into innovation dynamics on platform ecosystem and practical implications for firms seeking to optimize their innovation strategies through strategic management of both user and producer modification pathways.

1. Introduction

Product users have long been recognized as an important source of innovation that can augment producer innovation (von Hippel, 1986; Von Hippel, De Jong, & Flowers, 2012). Researchers have studied what drives user innovation (de Jong & von Hippel, 2009; Morrison, Roberts, & von Hippel, 2000), and how a producer can influence its users' innovation activities to its own advantage (Berthon, Pitt, McCarthy, & Kates, 2007; Lilien, Morrison, Searls, Sonnack, & Hippel, 2002; Nambisan, Agarwal, & Tanniru, 1999). However, there is still much ambiguity about how producer innovation and user innovation relate to each other, especially regarding the question of whether they act as substitutes or complements for each other. This question is important because it may influence innovation investments and activities of both users and producers, may shape producers' policies toward and interactions with their users, may accelerate, decelerate, or redirect product evolution trajectories, and thus may drive the user value proposition, competitive advantage, and performance of producers. If the relationship between user and producer innovation is complementary, both sides may benefit. On the producer's side, these benefits of complementarity may include importing free or low-cost R&D, raising entry barriers, differentiating its product, lengthening its product's lifespan, or broadening its product's market to include new types of users with different applications. On the users' side, these benefits of complementarity may include enjoying improved or customized experiences that would not be possible without piggybacking on the producer's efforts, being empowered to solve niche problems for rare conditions/uses that would otherwise be ignored, exercising creative freedom, and perhaps even monetizing their innovations by sharing them with the producer or with fellow users. On the other hand, however, if user and producer innovation are substitutes, then both sides may suffer hazards. On the producer's side, these hazards may include undermining its intellectual property, its technology leadership position and reputation, and its revenue streams. On the users' side, these hazards may include the threat of legal action due to ambiguity about whether a user's innovation violates its contractual obligations to the producer or infringes on the producer's intellectual property, as well as market counterattacks if the user innovation is monetized in ways that compete with the producer. The question of whether user and producer innovation complement or substitute for each other may also be important to public policy, since it may affect the pace of technical advancements, the fairness and intensity of competition, and the accessibility of solutions for niche problems and applications. So, overall, the interaction between producer and user innovation may help dictate who drives progress and in what direction, how democratized innovation is, how much value it creates, and who captures that value.

So far, research on the interaction between user innovation and producer innovation has produced ambiguous and conflicting results (Baldwin & von Hippel, 2011; Bogers, Afuah, & Bastian, 2010; Randhawa, Wilden, & Hohberger, 2016; West & Bogers, 2014), perhaps because the research question has not yet been clearly articulated. On one hand, some studies observe a trend in which user-driven forms of open innovation are increasingly substituting for producer innovation (Baldwin & von Hippel, 2011; Greul, West, & Bock, 2018; Henkel, Schöberl, & Alexy, 2014; Shah & Tripsas, 2007; Von Hippel, 2005). For example, Baldwin and von Hippel (2011) suggest that users' innovation-cost advantages may allow user-driven innovations to proliferate rapidly and displace producer innovation. Similarly, Shah and Tripsas (2007, 2016) study the emergence of user entrepreneurs who move beyond merely innovating for their own personal use to commercializing their user innovations in ways that may substitute for, and even compete with, the producer's original product. On the other hand, some studies focus on ways in which user innovation complements producer innovation (Borner, Berends, Deken, & Feldberg, 2023; Hienerth, Lettl, & Keinz, 2014; King & Lakhani, 2013; Laursen, 2011; von Hippel, 2017). For example, Laursen (2011) finds that user and producer innovation complement each other in the sense that they differ in the breadth and goals of their search strategies, and therefore often wind up also differing in their scope and/or purpose. Similarly, King and Lakhani (2013) and Borner et al. (2023) find that user innovation can identify new ideas, combinations, and opportunities that producer innovation can subsequently exploit – i.e., a sequential form of complementarity.

A key conceptual problem in this research stream – which has impeded progress toward answering the question of whether and when user innovation and producer innovation are complements or substitutes – is that prior literature has not clearly distinguished between two distinct domains in which users and producers can focus their innovation efforts – namely, development of new products versus modification of existing products. In other words, although the prior literature discusses differences between users and producers in their respective motivations, capabilities, and knowledge bases, and although it also examines mechanisms affecting the interaction between users and producers as sources of innovation (Bogers et al., 2010; Von Hippel, 2005), it nevertheless neglects to control for a key contingency – the domain of the innovation activity itself. This omission has prevented prior research from measuring user innovation and producer innovation, as well as their joint effects, as an apples-to-apples comparison on a level playing field. This, in turn, has made it impossible for prior research to cleanly distinguish the effect of the source of innovation (i.e., users versus producers) from the effect of the domain of innovation (i.e., product development versus product modification). It is therefore unsurprising that prior research on this question has produced such ambiguous and conflicting results.

Table 1: Framework for Producer/User Innovation Domains & Their Interactions

		Users' Innovation Domain	
		Product Development	**Product Modification**
Producer's Innovation Domain	**Product Development**	***User Entrepreneurship*** Producer & user innovation act as substitutes.	***Innovation Ecosystem*** Producer & user innovation act as complements.
	Product Modification	***Innovation Backflow*** Producer & user innovation act as complements.	***Downstream Co-Creation*** Ambiguous: Producer & user innovation may act either as substitutes or as complements.

As shown in Table 1, if we combine the two sources of innovation (producers and users) with the two domains of innovation (product development and product modification), there are four scenarios where user innovation might interact with producer innovation, and these four scenarios have different implications for whether they are substitutes or complements. Consider each of these four scenarios in turn.

The scenario in the top-right cell of Table 1, where producers innovate in product development and users innovate in product modification, captures the classic archetype of an innovation ecosystem (Adner, 2006; Granstrand & Holgersson, 2020) with a central orchestrating firm developing a base product upon which users can attach their own modifications. In innovation ecosystem research, it is common to call such users "complementors" whose modifications are called "complements." So, naturally, one would expect that, in this archetypical innovation ecosystem scenario (top-right cell of Table 1), producer and user innovation are complementary in general – although there may, of course, be exceptions to this rule.

In Table 1's top-left cell, where producers and users both innovate in product development, this scenario captures user entrepreneurship as described by Shah and Tripsas (2007, 2016) and exemplified by user innovation in markets for board sport equipment like surf boards (Diaz Ruiz & Makkar, 2021). Since such product-development innovations from users usually compete directly with those of producers, it is natural to view them as substitutes in general – although there may, of course, be exceptions to this rule.

Table 1's bottom-left cell represents, in effect, a role reversal from the classic innovation ecosystem archetype. Whereas classic innovation ecosystems feature a producer's product-development innovations being adopted by a set of "complementor" users engaged in product modification, the bottom-left cell, by contrast, offers a scenario where it is the users who innovate through product development innovation and the producers who innovate through product modification. For convenience, we label such scenarios as "innovation backflow" to capture the idea that they reverse the usual expected directional flow of innovation in classic archetypical ecosystems. Such innovation backflow scenarios may be rarer than classic innovation ecosystems, but they do occur.[1] As indicated by King and Lakhani (2013) and Borner et al. (2023), the

[1] For example, some open-source software tools like Linux and MySQL were originally developed by hobbyist users, but then later modified, refined, and enhanced by companies like Red Hat (with Linux) or Oracle (with MySQL) into enterprise-grade commercial products. Similarly, technologies pioneered by biohacking citizen-science projects like the Open Artificial Pancreas

relationship between user and producer innovation in such innovation-backflow scenarios would generally be expected to be complementary – although there may, of course, be exceptions to this rule.

Finally, the bottom-right cell is where we find the only real ambiguity anywhere in Table 1. The other three cells offer scenarios in which it is reasonably clear whether user and producer innovation are unambiguously expected to usually act as complements or substitutes (with some possible exceptions, of course), but the scenario in the bottom-right cell is highly ambiguous. This scenario, where both users and producers innovate via product modification, is a special case of co-creation (Buur & Matthews, 2008; Prahalad & Ramaswamy, 2000), which has been defined as "enabling users to autonomously experiment and innovate by providing a platform for collaborative innovation, for example by hosting user communities or providing 'toolkits' for innovation" (Bogers et al., 2010: 865). Specifically, because the focus in this cell is on product modification rather than new product development, we label it as downstream co-creation, in the sense that modification of a product is downstream from its original development. In this scenario, it is unclear whether user and producer innovation are complements or substitutes because this situation – in which users and producers are both innovating via product modification – is where the two sides are closest to being on a "level playing field" with each other. A producer's product modification may substitute for a user's product modification if the two are sufficiently similar, but alternatively, they may complement each other if they are sufficiently different in their scope and/or purpose, as in Laursen (2011).

The key empirical contribution of the present paper is to focus specifically on this downstream co-creation scenario, where the ambiguity is greatest because users and producers are closest to being on a level playing field. In other words, the present study assumes the challenge of providing clarity about the specific cell in Table 1 that is the most unclear. It does so by leveraging rich data in the empirical context of

---

System have been coopted into commercial products by medical device companies like Medtronic. Likewise, the 3D printing revolution originated from open-source communities of hobbyists like the RepRap Project before being refined and enhanced into commercial products by companies like Prusa Research and Ultimaker. Finally, many popular Hollywood movies have been based on novels that were originally self-published by their authors, including Andy Weir's *The Martian*, E.L. James's *Fifty Shades of Grey*, and Amanda Brown's *Legally Blonde*.

the Steam platform for PC video games, where both game developers (producers) and players (users) can create innovative product extensions for the same games – which are called downloadable content (DLC) for product extensions that developers sell and user-generated content (UGC) for product extensions that users can share (and sometimes sell) via the Steam Workshop system, which enables videogame developers to easily transform their products into micro-platforms for users' sharing of UGC. This large-scale empirical context offers the unique advantage of analyzing innovations that are reasonably similar between users and producers because they are both in the domain of product extensions and are both extending the same base product. This similarity between producers' DLC and users' UGC allows the study to isolate the specific effects attributable solely to the source of innovation (i.e., user versus producer), without being confounded by differences in the domain of innovation (i.e., product development versus product modification). In other words, this unique empirical setting is as close as one can reasonably find to an apples-to-apples level playing field for measuring user innovation, producer innovation, and their joint effects.

2. Literature Review: User and Producer Innovation in Downstream Co-Creation

The term co-creation has been used to refer to a broad range of practices in which producers and users jointly contribute to producer-led innovation, but different research streams emphasize different aspects of it. Open innovation scholars focus on governance aspects: how producers benefit when users participate in the innovation process, either through the lead users approach—gathering insights from advanced users at the market's edge (Hienerth et al., 2014; Lilien et al., 2002; von Hippel, 1986), or through platforms enabling autonomous user innovation by hosting user communities (Jeppesen & Frederiksen, 2006). Meanwhile, user engagement researchers emphasize interaction patterns: how to foster bidirectional exchanges of new product ideas between users and producers during co-creation (Piller & Walcher, 2006; Ramaswamy, 2009; Sawhney, Verona, & Prandelli, 2005; Schweisfurth & Dharmawan, 2019; Trischler, Pervan, & Scott, 2017), contrasting with unidirectional approaches like simple product customization (Stojčić, Dabić, & Kraus, 2024).

Despite these divergent emphases, a notable commonality across the co-creation studies is that the majority of these practices seem to be focused on upstream development of new products. As Stojčić et al. (2024: 3) observe, "the literature on user engagement in innovation held that their contributions are mainly concentrated in the front-end stages of innovation process such as idea and concept development or creative thinking." A similar pattern appears in open innovation literature, where research primarily emphasizes users' contributions to the front-end stages of new product development through idea generation and selection (King & Lakhani, 2013). This shared emphasis on early-stage innovation reflects the widespread perception that user input delivers its greatest value during ideation and conceptualization phases, before products are fully defined or developed. While studies on complementary innovation apply to both pre-launch and post-launch phases of a product's life cycle, there remains a significant gap in understanding how co-creation might work after launch, i.e., when existing offerings need improvement and adaptation rather than complete reimagining. This gap provides an additional motivation to extend the co-creation concept by applying it further downstream, to the domain of modifying or upgrading an existing product rather than developing a new product. As a special case of the broader co-creation phenomenon, the concept of downstream co-creation would specifically require both producers and users to innovate in the same domain – creating modifications or add-ons for the same focal product - and would typically encompass joint efforts to enhance, customize, or expand the functionality of established products already in use by customers. Importantly, users and producers may both commercialize their modification innovations for the same product.

This approach, combined with a unique empirical setting that provides a nearly ideal apples-to-apples comparison, allows me to examine user-producer interaction patterns attributable solely to the innovation source (user versus producer), without being confounded by differences in innovation domain (product development versus product modification).

3. Theory Development and Hypotheses

3.1 Adopting Product-Modification Policies Versus Innovating Actual Product Modifications

By focusing on downstream co-creation, this study is limited only to innovations in the domain of product modification, regardless of whether they are innovated by users or producers. So, it is important to understand the preconditions that either support such modifications to occur in the first place or impede them from occurring. Many of these preconditions are under the direct control of the product's producer, in which case they can be called product-modification policies, either modification-supporting or modification-impeding in nature. Perhaps the most fundamental modification-supporting policy that a producer can adopt is modular product design. Modularity is a cornerstone enabler for anyone, whether producer or user, to modify an existing product, because it greatly reduces the amount of technical skill that such modification requires (Baldwin & Clark, 1999). After all, if a product is designed in a non-modular fashion, then any attempt to modify it must address the product as a complete system, accounting for myriad, complex, and potentially unpredictable ways in which tinkering with any one part might impact any other part. By contrast, effective modular design regulates interactions between the product's modules, thereby restraining such ripple effects, or at least making them more predictable. This allows modification efforts to concentrate at the component or subsystem levels, with less concern about systemwide spillovers, which in turn fosters a product-modification division of labor, where specialists build expertise in modifying particular components or subsystems while having less need to interact with experts who specialize in modifying other components or subsystems (Hoopes & Postrel, 1999; Postrel, 2002, 2009), and such division of labor can benefit productivity.

Although modular product design is a foundational modification-supporting policy, it may not be sufficient to ensure that actual product modifications will be created and commercialized, either by users or producers, so producers may also adopt additional product-modification policies. For example, the producer's revenue model may determine whether its own innovation efforts are focused relatively more on modifying existing products versus developing new products. On one hand, a "pay-to-play" revenue model usually encourages a producer to focus on developing complete products that get periodically improved over time in the hope of persuading users to upgrade to a whole new version (Rietveld, 2018). So, pay-to-play monetization tends to function as a producer-modification-impeding policy, which can be recognized by the producer's choice to avoid selling extensions or accessories to its product. On the other hand, a "freemium" or loss-leader revenue model usually encourages a producer to focus on crafting modifications to its existing product in the hope of persuading users to purchase them in a piecemeal mix-and-match manner to build their own unique installations customized with the specific features that they each individually value (Rietveld & Ploog, 2021). So, this monetization approach tends to function as a producer-modification-supporting policy, which can be recognized by the producer's choice to sell extensions or accessories to its product.

In addition to policies that shape its own product-modification efforts, a producer may also adopt policies that shape users' product-modification efforts. These policies can be technical, commercial, or legal in nature. On the technical side, a producer who uses industry-standard interfaces with publicly available specifications is adopting a pro-user-modification policy (Felin & Zenger, 2014; West & Bogers, 2014). Producers may also actively support users' product modification efforts by publishing detailed product designs, schematics, application programming interfaces (APIs), or software development kits (SDKs), or by offering consulting services, training programs, or other forms of technical assistance (Franke & Von Hippel, 2003; Jeppesen & Frederiksen, 2006). In terms of commercial policies, a pro-user-modification producer may even provide a platform to serve as a distribution channel for users to share their modifications with other users (Hagiu & Altman, 2017; Zhu & Furr, 2016), as in our empirical context, or may even subsidize user modification efforts by offering rewards, prizes, or certifications (Aguiar & Waldfogel, 2018; Elfenbein, Fisman, & McManus, 2015; Rietveld, Schilling, & Bellavitis, 2019). In terms of legal policies, a producer may support user modification by licensing out a product's intellectual property, especially on an open-source basis.

By contrast, a producer who opposes user modifications, and wishes to actively impede them, may likewise adopt anti-user-modification policies of a technical, commercial, or legal nature. On the technical side, using nonstandard proprietary interfaces and keeping the specifications for those interfaces private would be an anti-user-modification policy. An anti-user-modification producer may retain enough technical control over the product to be able to restrict its features or even disable it completely if a user modifies it (sometimes known as “bricking” a product). In terms of legal policies, aggressively enforcing intellectual-property rights is an anti-user-modification policy (Laurent, 2004). In terms of commercial policies, producers who oppose user innovation often implement a policy of voiding the warrantee for user-modified products. In terms of legal policies, they may impose contractual restrictions that limit users’ rights to change (or perhaps even repair) a product, or that dictate what kinds of modifications are allowed, or that charge fees for modifications (Bauer, Franke, & Tuertscher, 2016). Some may even by lobby for government regulations with these same effects (perhaps rationalized by an appeal to public safety or consumer protection).

A producer’s product-modification policies are different than the actual product modifications themselves. So, an open question is whether the relationship between a producer’s product modifications and its users’ product modifications will necessarily mirror the relationship between producer-modification-supporting policies and user-modification-supporting policies. One might naturally expect that if users’ product modifications and a producer’s product modifications are complements (or, alternatively, are substitutes), then policies supporting users’ product modifications will also be complementary (or, alternatively, substitutive) with policies supporting producers’ product modifications, and vice versa. However, this correspondence might not necessarily happen, and it is ultimately an empirical question.

This study attempts to answer this question by conducting two separate but related empirical inquiries. The first inquiry investigates the cross-sectional relationship between a producer’s choice of whether to adopt user-modification-supporting policies and its choice of whether to adopt of producer-modification-supporting policies. The second inquiry investigates (for a set of producers who have already adopted both of these policies) the dynamic relationship between the volume of user modifications and the volume of producer modifications, as these modifications accumulate over time. The relationship between the respective policies supporting these two sources of modifications may be different than the relationship between the respective volumes of innovation from these two sources. It is conceptually and empirically possible that one of these relationships may be complementary while the other is substitutive. This dual focus—both on the initial policy decisions and on the subsequent innovation activities—provides a more complete understanding on the mechanisms underlying user-producer downstream co-creation.

3.2 Alternative Interpretations of the Distinction Between Complements and Substitutes

Before proceeding to develop hypotheses, it is important to observe that there are two possible ways to define the distinction between complements and substitutes – by the impact of product modification by one source on product modification by the other source, or by their joint impact on performance. These two approaches may or may not be connected to each other, so it is helpful to avoid conflating or confusing them.

On one hand, the distinction may be defined by the impact of product modification by one source on product modification by the other source. Under this approach, these two sources of innovation would be seen as complementary if higher levels of activity in one of them (or adopting one policy) prompted higher levels of activity in the other (or adopting the other policy) – i.e., if both sources of innovation move in the same direction. Conversely, under this approach, they would be seen as substitutes if higher levels of activity in one of them (or adopting one policy) prompted lower levels of activity in the other (or adopting the other policy) – i.e., if the two sources of innovation move in opposite directions.

On the other hand, the distinction may be defined by joint impact of product modifications by both users and products on performance. Under this approach, innovating actual product modifications (or adopting product-modification policies) by users or producers would be seen as complementary if they have a positive interaction effect on performance – i.e., if the performance benefit of having more of one source of innovation (or adopting one policy) becomes larger in the presence of more of the other source of innovation (or adopting the other policy) (Athey & Stern, 1998; Cassiman & Valentini, 2016; Milgrom & Roberts, 1990). Conversely, under this approach, producer and user innovation would be seen as substitutes if they have a negative interaction effect on performance – i.e., if the performance benefit of having more of one source of innovation becomes smaller in the presence of more of the other source of innovation.

It is plausible to expect that if the two sources of innovation are complementary under one of these definitional approaches, then they would also be complementary under the other, and that if they were substitutes under one definitional approach, then they would also be substitutes under the other. However, there is no necessary reason why it must happen that way. In other words, if the two sources of innovation are complementary under one definitional approach, it is certainly possible that they might be substitutes under the other definitional approach. For this reason, the design of this study attempts to complementarity/substitutability of the two sources of innovation under both definitional approaches – including developing separate hypotheses, applying different identification strategies and testing the results with appropriate data and methods for each approach.

3.3 Adoption of Policies Regarding Product Modifications by Users and Producers

On one hand, supporting users' creation of extensions and modifications relieves producers from allocating resources to incremental development while simultaneously maintaining user engagement with existing products at lower production cost. These useful user innovations for product modifications may render subsequent producer innovations for modifications unnecessary, particularly when producers are already investing in multiple other product development initiatives. Although producers can potentially identify commercial opportunities from user innovations and decide to commercialize a better version of it—as King and Lakhani (2013) demonstrate that user innovations effectively reveal novel ideas and combinations for potential commercialization, a producer's willingness to capitalize on these opportunities will be constrained by both efficiency concerns and strategic considerations aimed at preserving existing user engagement and creativity. From an efficiency standpoint, the market potential of commercializing improved versions of user innovations may not offset the combined costs of innovation development and potential user attrition. This mechanism parallels Shah and Tripsas (2007)'s observation that user innovations often thrive in market niches too small to attract producer entry. Therefore, we hypothesize that:

H1: The likelihood of adopting a policy of producer innovation for product modification decreases as the likelihood of adopting a policy of user innovation for product modification increases.

On the other hand, producer decisions on enabling users to engage in product modification innovation for the focal product are significantly influenced by their endorsed technical capabilities. Greul et al. (2018)'s qualitative research on 3D printer startups revealed that producers with stronger technical capabilities and robust intellectual property (IP) protections are less inclined to incorporate knowledge from open user communities. This suggests that as producers develop stronger internal innovation competencies that are well protected by its IPs, they become less dependent on adopting external user contributions. Consequently, the motivation to embrace users for extra product modification decreases as a producer's own innovation likelihood increases. Therefore, we hypothesize that:

H2: The likelihood of adopting a policy of user innovation for product modification decreases as the likelihood of adopting a policy of producer innovation for product modification increases.

Having considered how decisions to adopt policies for user product modification and producer product modification affect each other bidirectionally, we now turn to examining the performance implications of these policy adoption decisions. Although producers who commit to their own product-modification innovations may be less likely to adopt policies for users' product-modification innovations, nevertheless adopting user innovation represents an additional stream of market-driven value creation that can significantly enhance firm performance. Users may contribute to overall product development by making their complementary innovations freely available to the firm's customer base, thereby creating strong network effects that enhance the perceived value of the core product (Katz & Shapiro, 1994). Furthermore, in cases where developers enabled users to engage in product modifications for the focal product upfront, they may be strategically deterred from pursuing their own modification innovations that could alienate existing user innovators. Nevertheless, by expanding the solutions available to the current customer base and potential future customers, this approach can catalyze another cycle of performance improvement, therefore resulting in overall better firm performance. Therefore, we hypothesize that:

H3: The performance benefit of adopting product modification by users becomes larger in the *presence of product modification by producers, and vice versa.*

3.4 Interplay Between Volumes of Product Modifications by Users and Producers

Volumes of product modifications by users complement subsequent volumes of product modifications by producers. On one hand, product modifications by users serve as a powerful complement to product modifications by producers through providing valuable external knowledge that reduces R&D uncertainty and costs. These modifications by users effectively function as real-world "test markets," allowing producers to accurately assess market potential before committing substantial resources to modification and commercialization efforts (Gambardella, Raasch, & von Hippel, 2017). On the other hand, producers can strategically incorporate successful features from users' modifications into their subsequent modifications to maintain market position and protect their proprietary focal products.

However, the positive effect of user modifications on subsequent producer modifications may be only up to certain point since the solution spaces in the existing focal product will reach its own limit. Therefore, as the existing volumes of product modifications by users increase, negative incentives to create subsequently more volumes of product modifications by producers will prevail. Therefore, we hypothesize that:

H4: Volumes of product modifications by users have a positive impact on the subsequent volumes of product modifications by producers up to a certain threshold but have a negative impact beyond that threshold.

Volumes of product modifications by producers may have more complex effects on volumes of product modifications by users. As producers intensify product modifications, they may eventually "crowd out" product modifications by users through several mechanisms. First, when producers expand their modification innovation offerings, they tend to reduce the "solution spaces" or "blank spots" that typically motivate user creativity. Second, increased product modifications by producers often expand proprietary technology boundaries, potentially restricting access to APIs or development tools that users require for their modification innovations, thereby raising barriers to user participation. Third, creating user modifications becomes increasingly difficult or costly as producer modification offerings become more sophisticated. As users' product modification costs exceed their expected benefits or utility, as suggested by Baldwin and von Hippel (2011)'s model, users may be deterred from engaging in subsequent modification activities.

However, above negative effect will be moderated by prior volumes of product modifications by users. When producer releases product modifications in contexts with a decent volume of prior product modifications by users, it likely serves a strategic purpose—to sustain existing user engagement and creativity rather than a monopolist replacement. With this purpose in mind, producers deliberately preserve creative white spaces, functioning as catalysts for continued user innovation. Conversely, when producer releases product modifications in contexts with no or minimal product modifications by users, it could worsen the situation by crowding out simple solution spaces as we mentioned before. Therefore, we hypothesis that:

H5: Volumes of product modifications by producers have a negative impact on the subsequent volumes of product modifications by users. This negative main effect will be positively moderated by the volumes of prior product modifications by users.

Having established how volumes of product modification by producers and by users affect each other, we now turn to examine the performance implications of these two sources of product modification innovation. When users create product modifications with few volumes of product modifications by producers, they often encounter what Laursen (2011) identifies as innovation conservatism— a limiting pattern characterized by narrower scope and less sophisticated enhancements that ultimately fail to realize the focal product's full potential. When producers develop product modifications with few users' involvement, they confront a significant dual challenge that often leads to resource misallocation and subsequent performance deterioration. First, they lack enough insights into users' needs and preferences, as this knowledge is often tacit and difficult to articulate or transfer (Von Hippel, 2005). Second, the focal product lacks the necessary user engagement and attractiveness to sustain future modification efforts, creating a problematic foundation for continued product development investments. Therefore, we hypothesize that:

H6: The performance benefit of having more of product modification by users becomes larger in the presence of more of product modification by producers, and vice versa.

4. Empirical Context and Data Description

We assembled a unique data set that exploits a recent innovation in the videogame industry. Specifically, in early 2015, Valve Corporation's Steam videogame platform made the Steam Workshop feature widely available for all videogame developers to open their games for digital artists to upload user-generated content (UGC), such as levels, vehicles, weapons, skins etc. and share them with players who can use them within the focal game. The videogame developer decides how the submitted UGC can be approved and monetized – either via a "curated workshop" where approval is governed by the game developer and/or the players themselves, or via a "ready-to-use workshop" where all uploaded UGC is automatically available to anyone. In effect, the Steam Workshop tool enables a videogame developer to transform her game into a micro-platform for its players to share user innovations (UGC) with each other. This tool makes it quick and easy for game developers – even those with small and under-resourced teams – to incorporate a complex and sophisticated platform feature that would otherwise require a significant investment of personnel effort.

Steam Workshop has thus become the most powerful tool in the videogame industry (and perhaps in any industry) to enable producers to give their users a platform for sharing user innovations. Over 4300 games were available on Steam at the time when Steam Workshop became available to all videogame developers, and over 200 of them subsequently adopted the Steam Workshop feature. By 2023, over 66,000 games were available on Steam, over 2100 of which had adopted Steam Workshop. In addition to this possibility of opening their games for add-on UGC complements, videogame developers can also sell their own add-on complements for their games, known as downloadable content (DLC), such as new story sequels, new characters, or new equipment like weapons or vehicles. We collected detailed data about every game available on Steam, regardless of whether it uses Steam Workshop or not, as well as detailed data about every item of Steam Workshop UGC (over 3.8 million) and about every piece of DLC (over 40,000).

To test our hypotheses for both adopting product-modification policies and innovating actual product modifications, we constructed two datasets: The first dataset comprises all games released after March 2015 (March 2015 to December 2023), when the Steam Workshop feature was widely available for developers to adopt if they wished. (The option for developers to offer producer innovations via DLC had always been available.) This cross-sectional dataset allows for testing hypotheses about game developers' adoption policies for product modifications by users and/or producers, across the full population of games released after March 2015 (in total 62083 games). The second dataset focuses exclusively on a subsample of games released between March 2015 and December 2023 but that have adopted policies supporting product modification by both users (enabling Steam Workshop for UGC) and by the producer (via DLC). So, in this subsample, we start observing a videogame at the earliest point in time when it both has at least one UGC and at least one DLC. This longitudinal dataset tracks quarterly innovation activities for modifications of each game, enabling us to test dynamic hypotheses about how the volumes of both user innovations and producer innovations accumulate over time. So, the first dataset addresses hypotheses on the complementarity versus substitutability issue in adopting product-modification policies (H1, H2, H3), whereas the second dataset supports analysis on complementarity/substitutability in innovating actual product modifications (H4, H5, H6).

Below is a brief summary of our key variables for each hypothesis. For detailed description on each variable construct, please refer to the comprehensive summary table for all variables. For H1, H2, H3 testing on complementarity/substitutability issue in adopting product-modification policies, both our independent variables and dependent variables are binary indicators capturing whether each game adopts product modification by users (via observing whether each game enables the "Steam Workshop" feature) and/or adopts product modification by producers (via observing whether each game has released at least one DLC). For H4, H5, H6 examining complementarity/substitutability issue on innovating actual product modifications, our independent and dependent variables measure the frequency of product modification by each source of innovation, operationalized as the quarterly aggregated count of UGCs and DLCs for each game over time. We measure performance using estimated units sold data and maximum concurrent count of users' data purchased from a data platform called VG insights[2]. Aside from above dependent and independent variables, to test the non-linear relationship in H4, we include the squared term of UGC count. To test the moderator in H6, we interact prior count of UGC with prior count of DLC.

We include several common control variables that affect the adoption of product-modification policies. First, we control for monetization strategies each game adopts when analyzing product-modification policies, measured by game price; as shown previously, different monetization approaches tend to affect a producer's incentive to adopt product-modification policies in various ways (Rietveld, 2018; Rietveld & Ploog, 2021). Second, we control for game genre (by counting each game's social features), since different types of games (i.e., single player game versus multiplayer game) have different innovation needs (Rietveld & Ploog, 2021).

When testing the complementarity/substitutability issue in volumes of product modifications, we employ game fixed effects to control for time-invariant game-level factors and include game age as a control. We further interact game age with contemporaneous dependent variables to account for changing innovation patterns throughout a game's lifecycle. Below is a summary table for all variables and their summary statistics.

Table : Summary of All Variables

Name	Variable Meaning	Measurement	Variable Type
$Adoption\ of\ \mathrm{DLC}_i$	adopting producer modification innovation (producer's decision)	0,1 binary	Endogenous dependent variable
$Adoption\ of\ UGC_i$	adopting user modification innovation (producer's decision)	0,1 binary	Endogenous dependent variable
$Ln(Totalunitssold)_i$	Performance metrics on sales	Natural log of total units	Endogenous

[2] VG insights' official website (https://vginsights.com/about) promises "estimates are within ±15% margin of error at an individual games data level for 84% of the games on Steam. At an aggregate level, the estimates are within ±5% margin of error."

	of games at December 2023	sold of each game at December 2023	dependent variable
$Ln(CCUmax)_i$	Performance metrics on maximum concurrent count of users as a proxy for user engagement at December 2023	Natural log of Maximum concurrent count of users at December 2023	Endogenous dependent variable
$ActiveNews_i$	Count of years that a game developer has been actively releasing news until 2023	Count number of years that a game developer has been actively releasing news until 2023	Exogenous Instrument
$Price_i$	Price of a game at December 2023	Price of a game at December 2023	Common control variable
$SocialityFeature_i$	How social a game is	Count of all social features including Steam trading cards, Steam leaderboards, MMO, Multiplayer, etc.	Common control variable
$\boldsymbol{SteamDepend_i}$	How dependent on Steam platform the game is	Number of non-Steam distribution channels each game has	Exogenous instrument
$\boldsymbol{LevelEditor_i}$	Whether A game has Level Editor feature which would benefit users generating modification innovation if producer adopted user modification innovation	0,1 binary	Exogenous instrument
$Ln(DLCcount)_{it}$	Frequencies of producer modification innovation activities	Natural log of cumulative quarterly DLC count at time t	Serially cross-correlated dependent variable

$Ln(UGCcount)_{it}$	Frequencies of user modification innovation activities	Natural log of cumulative quarterly UGC count at each time t	Serially cross-correlated dependent variable
$Ln(CCUmax)_{it}$	Performance metrics on concurrent count of users as a proxy for user engagement at time t	Natural log of maximum CCU at each time t	Serially cross-correlated dependent variable
$Ln(Totalunitssold)_{it}$	Performance metrics on game sales at time t	Natural log of Cumulative total units sold at time t	Serially cross-correlated dependent variable
$Ln(DLCcount)_{i,t-1}$	One period lagged of $Ln(DLCcount)_{it}$	Natural log of Cumulative DLC count at time t-1	Independent variable
$Ln(UGCcount)_{i,t-1}$	One period lagged of $Ln(UGCcount)_{it}$	Natural log of Cumulative UGC count at time t-1	Independent variable
$Ln(CCUmax)_{i,t-1}$	One period lagged of $Ln(CCUmax)_{it}$	Natural log of maximum CCU at each time t-1	Independent variable
$Ln(Totalunitssold)_{i,t-1}$	One period lagged of $Ln(Totalunitssold)_{it}$	Natural log of Cumulative total units sold at time t-1	Independent variable
$Game\_age_{i,t}$	What is the age of a game at quarterly time t?	at each time t, deduct quarterly transformed release time from t.	Control variable

Table: Summary Statistics for Subsample to Study Strategic decisions over Adopting User-Producer Innovation

	Min	p25	Mean	p75	Max	SD	N
$Adoption\ of\ \mathrm{DLC}_i$	0	0	0.081	0	1	.273	62083
$Adoption\ of\ UGC_i$	0	0	0.025	0	1	.156	62083
$\boldsymbol{SteamDepend_i}$	0	0	1.205	2	40	2.785	62083
$Price_i$	0	.99	7.818	9.99	999.98	14.075	62083
$SocialityFeature_i$	0	0	1.010	2	6	1.131	62083
$\boldsymbol{ActivveNews_i}$	0	0	0.957	1	13	1.314	62083
$\boldsymbol{LevelEditor_i}$	0	0	0.025	0	1	.157	62083

Table : Summary Statistics for Subsample of Games that Engaged in Downstream Co-creation

Summary Statistics

Variables	Obs	Mean	Std. Dev.	Min	Max	Skew.	Kurt.
Ln(UGCcount)	5678	5.249	2.465	0	10.404	.063	2.29
Ln(DLCcount)	5678	.932	.958	0	4.143	.746	2.727
Ln(Totalunitssold)	5678	12.345	2.328	4.094	17.711	-.294	2.655
Ln(CCUmax)	5621	5.096	2.705	0	12.419	.139	2.274
Game_age	5678	12.21	7.767	0	34	.414	2.314

5. Methods

To test the hypotheses regarding the adoption of product-modification policies, we address two significant endogeneity concerns. First, firms make non-random adoption decisions based on unobservable characteristics, creating potential omitted variables bias (Bascle, 2008). Second, producers' policies about adopting user modifications or creating their own modifications are interdependent policies that must be solved simultaneously, as each policy affects the other, resulting in a simultaneous equation bias where each decision may influence the other (Hausman, 1983). This study implements Instrument variables approach as the core identification strategy in all estimations to handle those endogeneity issues (Bascle, 2008; Semadeni, Withers, & Trevis Certo, 2014).

For the adoption of policies regarding product modifications by users, we use level editor feature and developers' activeness in releasing news and announcements as instruments. Level editor features are valid indicators because they represent technical capabilities that create external pressure on game producers to adopt user-friendly modification policies, without directly influencing decisions about producer-controlled modifications. Games with level editors naturally attract modification communities, incentivizing developers to formalize user modification policies regardless of their stance on producer modifications. This relationship is further clarified by the natural separation in our data context: most DLC content consists of bundles and new storylines rather than maps or levels, while user-generated content primarily focuses on creating custom levels and maps—precisely what level editors enable. This natural distinction helps isolate level editors' direct effect on user modifications from their minimal impact on official DLC strategies. Developers' activeness in releasing announcements about changes to the main game signals their inclination to engage with users, which may lead to user modification policy adoption without necessarily affecting producer modification strategies. This communication serves primarily as a marketing channel through which developers promote their changes and attract user attention. This outward-facing communication strategy represents an effort to access and respond to the player community's desires, positioning announcement frequency as an indicator of developer-user engagement rather than a reflection of the developer's modification production pipeline.

For producer modification policies, we utilize one distinct instrument. Producers' dependence on Steam (inversely measured by additional distribution channels beyond Steam) serves as a valid instrument because Steam's platform governance exerts external pressure on producers' modification policies without directly influencing user-focused policies.

When testing on complements and substitutes by the impact of adoption of product modification by one source on adoption of product modification by the other source (H1, H2) in a simultaneous equation system of two, instead of a conventional 3SLS estimation that usually works for continuous variables, we implement a structural equation modeling (SEM) estimation (Muthén, 1984), and a bivariate probit estimation (van Wissen & Golob, 1990). In sum, the two equation systems used to test H1 and H2 are below:

$$Adoption\ of\ DLC_i = \beta_1 Adoption\ of\ UGC_i + \beta_8 SocialityFeature_i + \boldsymbol{\beta_9 SteamDepend_i} + Price_i + \varepsilon_i$$

$$Adoption\ of\ UGC_i = \beta_{10} Adoption\ of\ DLC_i + \boldsymbol{\beta_{13} ActiveNews_i} + \beta_{16} Price_i + \beta_{17} SocialityFeature_i + \boldsymbol{\beta_{19} LevelEditor_i} + \varepsilon_i$$

*, where variables in **bold** represent unique instruments for each equation.*

We implement the “productivity” approach that Cassiman and Valentini (2016) suggest to test whether adoption of policies regarding product modifications by users and producers are complementary or substitutes, based on their joint impact on performance (H3). This test examines whether adopting user modifications when producer modifications are already in place creates a higher incremental performance effect than implementing either type of modification in isolation—which would indicate complementarity between the two practices. Adoption of product modifications by users (Adopting user) and adoption of product modifications by producers (Adopting producer) are therefore complementary policies if the following inequality holds:

$$Performance\ (\text{Adopting User\&Adopting Producer}) - Performance\ (\text{Adopting User } only)$$
$$\geq Performance\ (\text{Adopting Producer})$$
$$- Performance\ (\text{Not adopting User\&}Not\text{ adopting Producer})$$

To test the hypotheses regarding the complementarity/substitutability issue on innovating actual product modifications (H4, H5, H6), we must address two significant methodological concerns: First, the non-random nature of innovation engagement by both firms and users creates significant endogeneity challenges, particularly regarding firm-side activities. Second, the interplay between product modification activities by these two sources is characterized by dynamic, bidirectional interactions that feature serial correlation and temporal evolution. Following Makadok and Walker (1996) and Makadok (1999)'s approach, we employ panel vector autoregression (VAR) analysis (Abrigo & Love, 2016; Makadok & Walker, 1996) to do the granger causality test (Granger, 1969), explicitly modeling the temporal dependencies while capturing the dynamic interplay between product modification activities by users and producers.

In sum, the entire four equations in the panel VAR analysis are:

$$Ln(DLCcount)_{it} =$$
$$= \alpha_1\ Ln(UGCcount)_{i,t-1} + \alpha_2 Ln(CCUmax)_{i,t-1} + \alpha_3 Ln(Totalunitssold)_{i,t-1}$$
$$+ \alpha_4 Ln(DLCcount)_{i,t-1} + \alpha_5\ Ln(UGCcount)_{i,t-1} * Ln(DLCcount)_{i,t-1}$$
$$+ \alpha_6 Game\_age_{i,t} + \alpha_7\ Ln(UGCcount)_{i,t-1} * Game\_age_{i,t} + \alpha_8 Ln(CCUmax)_{i,t-1}$$
$$* Game\_age_{i,t} + \alpha_9 Ln(Totalunitssold)_{i,t-1} * Game\_age_{i,t} + \alpha_{10} Ln(DLCcount)_{i,t-1}$$
$$* Game\_age_{i,t} + \alpha_{11}\ Ln(UGCcount)_{i,t-1}{}^2 + \delta_i + \varepsilon_{it}$$

$$
\begin{aligned}
Ln(UGCcount)_{it} \\
&= \alpha_{12}\, Ln(UGCcount)_{i,t-1} + \alpha_{13} Ln(CCUmax)_{i,t-1} + \alpha_{14} Ln(Totalunitssold)_{i,t-1} \\
&+ \alpha_{15} Ln(DLCcount)_{i,t-1} + \alpha_{16}\, Ln(UGCcount)_{i,t-1} * Ln(DLCcount)_{i,t-1} \\
&+ \alpha_{17} Game_{age_{i,t}} + \alpha_{18}\, Ln(UGCcount)_{i,t-1} * Game_{age_{i,t}} + \alpha_{19} Ln(CCUmax)_{i,t-1} \\
&* Game_{age_{i,t}} + \alpha_{20} Ln(Totalunitssold)_{i,t-1} * Game_{age_{i,t}} + \alpha_{21} Ln(DLCcount)_{i,t-1} \\
&* Game_{age_{i,t}} + \alpha_{22} Ln(UGCcount)_{i,t-1}{}^{2} + \delta_i + \varepsilon_{it}
\end{aligned}
$$

$$
\begin{aligned}
Ln(CCUmax)_{it} &= \alpha_{23}\, Ln(UGCcount)_{i,t-1} + \alpha_{24} Ln(CCUmax)_{i,t-1} + \alpha_{25} Ln(Totalunitssold)_{i,t-1} \\
&+ \alpha_{26} Ln(DLCcount)_{i,t-1} + \alpha_{27}\, Ln(UGCcount)_{i,t-1} * Ln(DLCcount)_{i,t-1} \\
&+ \alpha_{28} Game_{age_{i,t}} + \alpha_{29}\, Ln(UGCcount)_{i,t-1} * Game_{age_{i,t}} + \alpha_{30} Ln(CCUmax)_{i,t-1} \\
&* Game_{age_{i,t}} + \alpha_{31} Ln(Totalunitssold)_{i,t-1} * Game_{age_{i,t}} + \alpha_{32} Ln(DLCcount)_{i,t-1} \\
&* Game_{age_{i,t}} + \alpha_{33} Ln(UGCcount)_{i,t-1}{}^{2} + \delta_i + \varepsilon_{it}
\end{aligned}
$$

$$
\begin{aligned}
Ln(Totalunitssold)_{it} \\
&= \alpha_{34}\, Ln(UGCcount)_{i,t-1} + \alpha_{35} Ln(CCUmax)_{i,t-1} + \alpha_{36} Ln(Totalunitssold)_{i,t-1} \\
&+ \alpha_{37} Ln(DLCcount)_{i,t-1} + \alpha_{38}\, Ln(UGCcount)_{i,t-1} * Ln(DLCcount)_{i,t-1} \\
&+ \alpha_{39} Game_{age_{i,t}} + \alpha_{40}\, Ln(UGCcount)_{i,t-1} * Game_{age_{i,t}} + \alpha_{41} Ln(CCUmax)_{i,t-1} \\
&* Game_{age_{i,t}} + \alpha_{42} Ln(Totalunitssold)_{i,t-1} * Game_{age_{i,t}} + \alpha_{43} Ln(DLCcount)_{i,t-1} \\
&* Game_{age_{i,t}} + \alpha_{44}\, Ln(UGCcount)_{i,t-1}{}^{2} + \delta_i + \varepsilon_{it}
\end{aligned}
$$

However, two performance measurements are highly correlated (0.866, see below correlation table result), therefore we chose to run three equations only (each time include either one of the performance metrics) in the panel VAR analysis to avoid multicollinearity issue.

Table : Correlation Matrix for Subsample of Games that Engaged in Downstream Co-creation

	Ln(UGCcount)	Ln(DLCcount)	Ln(Totalunitssold)	Ln(CCUmax)	Game_age
Ln(UGCcount)	1	.313239801	.6202136512	.5945782405	.2509775266
Ln(DLCcount)	.313239801	1	.3448606106	.3500359029	.1627157435
Ln(Totalunitssold)	.6202136512	.3448606106	1	.8661557329	.2404884409
Ln(CCUmax)	.5945782405	.3500359029	.8661557329	1	.0484785057
Game_age	.2509775266	.1627157435	.2404884409	.0484785057	1

6. Results

6.1 Result on Adoption of Policies Regarding Product Modifications by Users and Producers

SEM results and Bivariate probit results predict the opposite of H1: adoption of policies regarding product modification by users has a strong positive effect on adoption of policies regarding product modification by producers.

SEM result support H2, but Bivariate probit predicts the opposite of H2. SEM predicts that adoption of policies regarding product modification by producers has a strong negative effect on adoption of policies regarding product modification by users. However, Bivariate probit predicts the opposite. Therefore, H1 and H2 are not consistently supported, and the model specification needs to be carefully reviewed.

SEM and Biprobit Model Results

	(1) SEM Model	(2) Biprobit Model
Adoption of DLC		
Adoption of UGC	0.196^{***}	1.893^{***}
	(0.014)	(0.032)
SteamDepend	0.016^{***} (0.000)	0.062^{***} (0.002)
SocialityFeature	0.031^{***}	0.174^{***}

	(0.001)	(0.006)
price	0.001***	0.005***
	(0.000)	(0.001)
_cons	0.015***	-1.822***
	(0.001)	(0.012)
Adoption of UGC		
Adoption of DLC	-0.026***	2.441***
	(0.004)	(0.036)
SocialityFeature	0.013***	0.103***
	(0.001)	(0.007)
price	0.000***	-0.001
	(0.000)	(0.001)
LevelEditor	0.453***	1.504***
	(0.004)	(0.041)
ActiveNews	0.011***	0.082***
	(0.000)	(0.005)
_cons	-0.011***	-2.529***
	(0.001)	(0.017)
/		
var(e.adoption of DLC)	0.069***	
	(0.000)	
var(e.adoption of UGC)	0.018***	
	(0.000)	
athrho		-13.011
		(60.265)
N	62083	62083
chi2		58539.075
p		0.000
ll	-538253.100	-19337.826

Standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01

The "productivity" approach analysis demonstrates complementarity across all examined samples: the full dataset of games released after March 2015, and three subsamples categorized by monetization strategy or feature set (pay-to-play games, games with in-app purchases, and games with level editors). We created these additional subsamples specifically to test whether complementarity findings remain consistent across different business models and game features. The results in Column 1.1 for the full sample reveal substantial sales effects: adopting user modification features alone increases units sold from approximately 16,577 to 87,334 (a 427% increase), while adopting producer modification features alone increases sales to approximately 173,852 (a 949% increase). Most significantly, implementing both modification policies together generates dramatically higher sales of approximately 576,668 units (a 3,378% increase). This performance pattern remains consistent across all subsamples, providing strong evidence that the benefits of user modification are enhanced by the presence of producer modification, and vice versa. These robust findings across diverse game subsets strongly support the third hypothesis (H3).

Result Table on "Productivity" Approach: Average units sold for each game

	(1.1) All games	(1.2) Only pay-to-play games	(1.3) Only games with in-app purchase	(1.4) Only games with level editor
Adopt both	576668.03 (393)	539302.84 (340)	3400000.00 (18)	645925.16 (164)
Adopt users only	87334.40 (1114)	87369.06 (1011)	57166.75 (17)	74309.85 (578)
Adopt producers only	173852.77 (4634)	159420.00 (3589)	704544.51 (350)	188274.76 (92)
Adopt neither	16577.63 (53193)	13931.46 (45251)	111619.51 (1255)	36041.92 (671)
Total No. of observations	62083	52045	1698	1560

Note: Number of observations of each cell is included in the paratheses.

Result Table on "Productivity" Approach: Average maximum number of Concurrent Count of Users for each game

	(2.1) All games	(2.2) Only pay-to-play games	(2.3) Only games with in-app	(2.4) Only games with level editor

			purchase	
Adopt both	2374.99 (393)	2480.33 (340)	10960.76 (18)	1848.21 (164)
Adopt users only	229.37 (1107)	244.70 (1004)	160.92 (17)	118.78 (575)
Adopt producers only	835.36 (4614)	698.96 (3569)	4881.19 (350)	788.97 (92)
Adopt neither	76.64 (52289)	44.36 (44358)	955.51 (1251)	99.96 (660)
No. of observations	62083	52045	1698	1560

Note: Number of observations of each cell is included in the paratheses.

6.2 Result on Interplay Between Volumes of Product Modifications by Users and Producers

We include a baseline model without controls (models 1 and 2) and a complete model with controls (models 3 and 4). Below is a brief summary on our preliminary results and interpretations regarding each hypothesis:

The Displacement Effect: DLC Cannibalizes UGC. In model (3) and (4) listed in the Panel VAR results table, there's consistent evidence that official producer-generated DLC content tends to displace or reduce user-generated content. H5 is strongly supported across both models.

No Significant Impact: UGC fails to influence DLC. In both models, not only is the result insignificant but also the sign of the coefficient on both UGC term and UGC squared term is inconsistent across specifications. Therefore, H4 is not supported.

Interaction Effects Matter. The positive coefficient on the interaction term of UGC and DLC in the last period suggests that while DLC may displace UGC, there are synergistic effects when both co-exist in the downstream product modification market. H6 is strongly supported across both models.

No Clear Performance Implications on DLC-UGC interaction. Both model (3) and (4) reveal that only the squared term for UGCs significantly affects game performance metrics such as concurrent users (CCU) and units sold, while the UGC-DLC interaction term shows non-significantly inconsistent effects. H7 fails to be supported.

Result Table: Panel VAR Models for Games that Engaged in Downstream Co-creation

	(1) Model 1: Baseline Without Controls; Sales of Games as Performance Measure	(2) Model 1: Baseline Without Controls; User Engagement as Performance Measure	(3) Model 2: Sales of Games as Performance Measure	(4) Model 3: User Engagement as Performance Measure
DLC				
L1. DLC	.828***	0.912***	0.028	0.122
	(0.061)	(0.036)	(0.159)	(0.326)
L1. UGC	-.085	-0.042**	0.009	-0.025
	(0.075)	(0.021)	(0.066)	(0.160)
L1. Unitssold	.152		0.273	
	(0.119)		(0.173)	
L1. CCUmax		-0.039		-0.025
		(0.061)		(0.053)
Game_age			-0.022**	-0.002
			(0.078)	(0.010)
L1. UGC_DLC			0.042	0.017
			(0.035)	(0.055)
L1. UGC_age			0.000	0.000
			(0.000)	(0.000)
L1. DLC_age			-0.004***	-0.004
			(0.001)	(0.002)
L1. Unitssold_age			0.002***	
			(0.000)	
L1. CCUmax_age				0.002***
				(0.000)
L1. UGC* L1. UGC			-0.004	0.016
			(0.018)	(0.011)
UGC				
L1. DLC	-0.079	0.027	-0.869***	-1.336**
	(0.081)	(0.061)	(0.164)	(0.435)
L1. UGC	0.749***	0.831***	0.601***	0.192
	(0.130)	(0.038)	(0.077)	(0.203)
L1. Unitssold	0.263		0.583***	
	(0.192)		(0.181)	
L1. CCUmax		-0.080		-0.121*
		(0.027)		(0.069)
Game_age			-0.009	0.038**
			(0.009)	(0.012)
L1. UGC_DLC			0.172***	0.223**
			(0.034)	(0.076)
L1. UGC_age			0.001	-0.003**
			(0.001)	(0.001)
L1. DLC_age			-0.004**	-0.009**
			(0.002)	(0.003)
L1. Unitssold_age			0.001**	
			(0.000)	
L1. CCUmax_age				0.001
				(0.001)
L1. UGC* L1. UGC			-0.060***	-0.008
			(0.018)	(0.016)
Unitssold				
L1. DLC	0.005		-0.142	
	(0.022)		(0.103)	
L1. UGC	-0.009		0.029	
	(0.035)		(0.042)	
L1. Unitssold	0.917***		0.992***	
	(0.051)		(0.108)	

L1. CCUmax				
Game_age			-0.009*	
			(0.005)	
L1. UGC_DLC			0.031	
			(0.022)	
L1. UGC_age			0.001*	
			(0.000)	
L1. DLC_age			-0.001	
			(0.001)	
L1. Unitssold_age			0.001**	
			(0.000)	
L1. CCUmax_age				
L1. UGC* L1. UGC			-0.189*	
			(0.011)	
CCUmax				
L1. DLC		0.438		-1.13
		(0.268)		(0.995)
L1. UGC		-0.20		-0.078
		(0.149)		(0.486)
L1. Unitssold				
L1. CCUmax		0.967***		0.212
		(0.173)		(0.171)
Game_age				-0.010
				(0.030)
L1. UGC_DLC				0.230
				(0.164)
L1. UGC_age				0.001
				(0.003)
L1. DLC_age				-0.011
				(0.007)
L1. Unitssold_age				
L1. CCUmax_age				-0.001
				(0.001)
L1. UGC* L1. UGC				-0.048*
				(0.028)
N. of Obs.	4970	4913	4970	4913
N. of Panels	338	338	338	338
Avg. no. of T	14.704	14.536	14.704	14.536
GMM Criterion Q(b)	0.00653	0.00401	0.00328	0.00851
Eigenvalue stability condition	✓	✓	✓	✓
Overidentifying Test	✓	✓	✓	✓
Game Fixed Effects	✓	✓	✓	✓

References

Abrigo, M. R., & Love, I. 2016. Estimation of panel vector autoregression in Stata. ***The Stata Journal***, 16(3): 778-804.

Adner, R. 2006. Match your innovation strategy to your innovation ecosystem. ***Harvard business review***, 84 4: 98-107; 148.

Aguiar, L., & Waldfogel, J. 2018. Platforms, promotion, and product discovery: Evidence from Spotify playlists: National Bureau of Economic Research.

Athey, S., & Stern, S. 1998. An empirical framework for testing theories about complimentarity in organizational design: National Bureau of Economic Research Cambridge, Mass., USA.

Baldwin, C., & von Hippel, E. 2011. Modeling a Paradigm Shift: From Producer Innovation to User and Open Collaborative Innovation. ***Organization Science***, 22(6): 1399-1417.

Baldwin, C. Y., & Clark, K. B. 1999. ***Design Rules: The Power of Modularity Volume 1***: MIT Press.

Bascle, G. 2008. Controlling for endogeneity with instrumental variables in strategic management research. ***Strategic organization***, 6(3): 285-327.

Bauer, J., Franke, N., & Tuertscher, P. 2016. Intellectual property norms in online communities: How user-organized intellectual property regulation supports innovation. ***Information Systems Research***, 27(4): 724-750.

Berthon, P. R., Pitt, L. F., McCarthy, I., & Kates, S. M. 2007. When customers get clever: Managerial approaches to dealing with creative consumers. ***Business Horizons***, 50(1): 39-47.

Bogers, M., Afuah, A., & Bastian, B. 2010. Users as Innovators: A Review, Critique, and Future Research Directions. ***Journal of Management***, 36(4): 857-875.

Borner, K., Berends, H., Deken, F., & Feldberg, F. 2023. Another pathway to complementarity: How users and intermediaries identify and create new combinations in innovation ecosystems. ***Research Policy***, 52(7).

Buur, J., & Matthews, B. 2008. Participatory Innovation. ***International Journal of Innovation Management***, 12(3): 255-273.

Cassiman, B., & Valentini, G. 2016. Open innovation: Are inbound and outbound knowledge flows really complementary? ***Strategic Management Journal***, 37(6): 1034-1046.

de Jong, J. P. J., & von Hippel, E. 2009. Transfers of user process innovations to process equipment producers: A study of Dutch high-tech firms. ***Research Policy***, 38(7): 1181-1191.

Diaz Ruiz, C., & Makkar, M. 2021. Market bifurcations in board sports: How consumers shape markets through boundary work. ***Journal of Business Research***, 122: 38-50.

Elfenbein, D. W., Fisman, R., & McManus, B. 2015. Market structure, reputation, and the value of quality certification. ***American Economic Journal: Microeconomics***, 7(4): 83-108.

Felin, T., & Zenger, T. R. 2014. Closed or open innovation? Problem solving and the governance choice. ***Research policy***, 43(5): 914-925.

Franke, N., & Von Hippel, E. 2003. Satisfying heterogeneous user needs via innovation toolkits: the case of Apache security software. ***Research policy***, 32(7): 1199-1215.

Gambardella, A., Raasch, C., & von Hippel, E. 2017. The user innovation paradigm: impacts on markets and welfare. ***Management Science***, 63(5): 1450-1468.

Granger, C. W. J. 1969. Investigating causal relations by econometric models and cross-spectral models. ***Econometrica***, 37: 424-438.

Granstrand, O., & Holgersson, M. 2020. Innovation ecosystems: A conceptual review and a new definition. ***Technovation***, 90-91: 102098.

Greul, A., West, J., & Bock, S. 2018. Open at birth? Why new firms do (or don't) use open innovation. ***Strategic Entrepreneurship Journal***, 12(3): 392-420.

Hagiu, A., & Altman, E. J. 2017. Finding the Platform in Your Product Four Strategies That Can Reveal Hidden Value. ***Harvard Business Review***, 95(4): 94-100.

Hausman, J. A. 1983. Specification and estimation of simultaneous equation models. ***Handbook of econometrics***, 1: 391-448.

Henkel, J., Schöberl, S., & Alexy, O. 2014. The emergence of openness: How and why firms adopt selective revealing in open innovation. ***Research Policy***, 43(5): 879-890.

Hienerth, C., Lettl, C., & Keinz, P. 2014. Synergies among Producer Firms, Lead Users, and User Communities: The Case of the LEGO Producer-User Ecosystem. ***Journal of Product Innovation Management***, 31(4): 848-866.

Hoopes, D. G., & Postrel, S. 1999. Shared knowledge, "glitches," and product development performance. ***Strategic Management Journal***, 20(9): 837-865.

Jeppesen, L. B., & Frederiksen, L. 2006. Why do users contribute to firm-hosted user communities? The case of computer-controlled music instruments. ***Organization Science***, 17(1): 45-63.
Katz, M. L., & Shapiro, C. 1994. Systems Competition and Network Effects. ***Journal of Economic Perspectives***, 8(2): 93-115.
King, A., & Lakhani, K. R. 2013. Using Open Innovation to Identity the Best Ideas. ***Mit Sloan Management Review***, 55(1): 41-48.
Laurent, A. M. S. 2004. ***Understanding open source and free software licensing: guide to navigating licensing issues in existing & new software***: " O'Reilly Media, Inc.".
Laursen, K. 2011. User-producer interaction as a driver of innovation: costs and advantages in an open innovation model. ***Science and Public Policy***, 38(9): 713-723.
Lilien, G. L., Morrison, P. D., Searls, K., Sonnack, M., & Hippel, E. v. 2002. Performance Assessment of the Lead User Idea-Generation Process for New Product Development. ***Management Science***, 48(8): 1042-1059.
Makadok, R. 1999. Interfirm differences in scale economies and the evolution of market shares. ***Strategic Management Journal***, 20(10): 935-952.
Makadok, R., & Walker, G. 1996. Search and selection in the money market fund industry. ***Strategic Management Journal***, 17(Summer special issue): 39-54.
Milgrom, P., & Roberts, J. 1990. The Economics of Modern Manufacturing: Technology, Strategy, and Organization. ***American Economic Review***, 80(3): 511-528.
Morrison, P. D., Roberts, J. H., & von Hippel, E. 2000. Determinants of User Innovation and Innovation Sharing in a Local Market. ***Management Science***, 46(12): 1513-1527.
Muthén, B. 1984. A general structural equation model with dichotomous, ordered categorical, and continuous latent variable indicators. ***Psychometrika***, 49(1): 115-132.
Nambisan, S., Agarwal, R., & Tanniru, M. 1999. Organizational Mechanisms for Enhancing User Innovation in Information Technology. ***MIS Quarterly***, 23(3): 365-395.
Piller, F. T., & Walcher, D. 2006. Toolkits for idea competitions: a novel method to integrate users in new product development. ***R & D management***, 36(3): 307-318.
Postrel, S. 2002. Islands of shared knowledge: Specialization and mutual understanding in problem-solving teams. ***Organization Science***, 13(3): 303-320.
Postrel, S. 2009. Multitasking Teams With Variable Complementarity: Challenges for Capability Management. ***Academy of Management Review***, 34(2): 273-296.
Prahalad, C. K., & Ramaswamy, V. 2000. Co-opting Customer Competence. ***Harvard Business Review***: 79-87.
Ramaswamy, V. 2009. Co-creation of value—towards an expanded paradigm of value creation. ***Marketing Review St. Gallen***, 26(6): 11-17.
Randhawa, K., Wilden, R., & Hohberger, J. 2016. A Bibliometric Review of Open Innovation: Setting a Research Agenda. ***Journal of Product Innovation Management***, 33(6): 750-772.
Rietveld, J. 2018. Creating and capturing value from freemium business models: A demand-side perspective. ***Strategic Entrepreneurship Journal***, 12(2): 171-193.
Rietveld, J., & Ploog, J. N. 2021. On top of the game? The

double-edged

sword of incorporating social features into freemium products. ***Strategic Management Journal***, 43(6): 1182-1207.
Rietveld, J., Schilling, M. A., & Bellavitis, C. 2019. Platform strategy: Managing ecosystem value through selective promotion of complements. ***Organization Science***, 30(6): 1232-1251.
Sawhney, M., Verona, G., & Prandelli, E. 2005. Collaborating to create: The Internet as a platform for customer engagement in product innovation. ***Journal of Interactive Marketing***, 19(4): 4-17.
Schweisfurth, T. G., & Dharmawan, M. P. 2019. Does lead userness foster idea implementation and diffusion? A study of internal shopfloor users. ***Research Policy***, 48(1): 289-297.
Semadeni, M., Withers, M. C., & Trevis Certo, S. 2014. The perils of endogeneity and instrumental variables in strategy research: Understanding through simulations. ***Strategic Management Journal***, 35(7): 1070-1079.
Shah, S. K., & Tripsas, M. 2007. The Accidental Entrepreneur: The Emergent and Collective Process of User Entrepreneurship. ***Strategic Entrepreneurship Journal***, 1(1-2): 123-140.

Shah, S. K., & Tripsas, M. 2016. When Do User-Innovators Start Firms? A Theory of User Entrepreneurship. ***Revolutionizing Innovation: Users, Communities, and Open Innovation***: 285-307.
Stojčić, N., Dabić, M., & Kraus, S. 2024. Customisation and co-creation revisited: Do user types and engagement strategies matter for product innovation success? ***Technovation***, 134: 103045.
Trischler, J., Pervan, S. J., & Scott, D. R. 2017. Exploring the “black box” of customer co-creation processes. ***Journal of Services Marketing***, 31(3): 265-280.
van Wissen, L. J., & Golob, T. F. 1990. Simultaneous‐Equation Systems Involving Binary Choice Variables. ***Geographical Analysis***, 22(3): 224-243.
von Hippel, E. 1986. Lead Users: A Source of Novel Product Concepts. ***Management Science***, 32(7): 791-805.
Von Hippel, E. 2005. Democratizing innovation: The evolving phenomenon of user innovation. ***Journal für Betriebswirtschaft***, 55: 63-78.
von Hippel, E. 2017. Free Innovation by Consumers—How Producers Can Benefit: Consumers’ free innovations represent a potentially valuable resource for industrial innovators. ***Research-Technology Management***, 60(1): 39-42.
Von Hippel, E., De Jong, J. P., & Flowers, S. 2012. Comparing business and household sector innovation in consumer products: findings from a representative study in the United Kingdom. ***Management Science***, 58(9): 1669-1681.
West, J., & Bogers, M. 2014. Leveraging External Sources of Innovation: A Review of Research on Open Innovation. ***Journal of Product Innovation Management***, 31(4): 814-831.
Zhu, F., & Furr, N. 2016. Products to Platforms: Making the Leap. ***Harvard Business Review***, 94(4): 72-78.