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journal homepage: [www.elsevier.com/locate/jfec](http://www.elsevier.com/locate/jfec)Token-based platform finance<sup>☆</sup>Lin William Cong<sup>a</sup>, Ye Li<sup>b,\*</sup>, Neng Wang<sup>c</sup><sup>a</sup> *Cornell University Johnson Graduate School of Management, United States*<sup>b</sup> *The Ohio State University Fisher College of Business, 2100 Neil Avenue, Columbus OH 43210, United States*<sup>c</sup> *Columbia Business School, ABFER, and NBER, United States*

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## ABSTRACT

We develop a dynamic model of a platform economy where tokens serve as a means of payment among platform users and are issued to finance investment in platform productivity. Tokens are optimally rewarded to platform owners when token supply (normalized by productivity) is low and burnt to boost franchise value when the normalized supply is high. Although token price is determined in a liquid market, the platform's financial constraint generates an endogenous token issuance cost that causes underinvestment through the conflict of interest between insiders (owners) and outsiders (users). Blockchain technology mitigates underinvestment by addressing the owners' time inconsistency problem.

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## 1. Introduction

Digital platforms are reshaping the organization of economic activities. Traditional platforms rely heavily on payment innovations to stimulate economic exchanges among users. Recently, blockchain technology offers alternative solutions. A new generation of digital platforms introduce crypto tokens as local currencies and allow the use of smart contracts to facilitate transactions among users, as well as the financing of ongoing platform development.

We develop a dynamic model of a digital platform to analyze the equilibrium dynamics of token-based communities. In our model, transactions on the platform are settled with native tokens. Users demand tokens as a means of payment, and their holdings are exposed to the fluctuation of token price. The entrepreneur (representing platform owners) manages token issuance by solving a dynamic problem of token-based payout and token-financed investment in platform productivity. The token market-clearing condition determines the evolution of the token price. The ratio of token supply to platform productivity (“normalized token supply”) is the key state variable. When it is high (i.e., the system is “inflated”), the platform cuts back investment and refrains from payout. To reduce token supply and boost token price, the platform may find it optimal to buy back tokens, but doing so requires costly external funds.<sup>1</sup> The financing cost of token buyback is the key friction that causes underinvestment in productivity. Our analysis applies to both traditional and blockchain-based platforms.

Our model delivers several unique insights on the economics of tokens and platforms. First, tokens are akin to durable goods but defy Coase’s conjecture (Coase, 1972). While the marginal cost of producing digital tokens is zero, the entrepreneur refrains from over-supply, and the equilibrium token price is positive. In contrast to the stationary demand in durable goods models (e.g., Stokey, 1981; Bulow, 1982), token demand grows endogenously as the platform invests in its productivity.<sup>2</sup> Under a growing token demand, the entrepreneur optimally spreads out token payouts over time, trading off between milking the system now or in the future. The entrepreneur balances the growth of token supply with productivity. Specifically, the productivity-normalized token supply is endogenously bounded.

Second, underinvestment arises from the conflict of interest between the entrepreneur and platform users. When tokens are issued to finance investment, token supply increases but the investment outcome is random. If productivity improves, both the entrepreneur and users benefit; otherwise, the users are free to reduce token holdings or even abandon the platform, while the entrepreneur, now facing an inflated system, may have to raise costly external

funds to buy back tokens. Such asymmetry dampens the entrepreneur’s incentive to invest. The underinvestment in turn reduces user welfare, the equilibrium token price, and eventually, the entrepreneur’s value from token payouts.

The root of the underinvestment problem is the entrepreneur’s time inconsistency. If the entrepreneur is able to commit against underinvestment, the users would demand more tokens, which then increases the token price and the value of entrepreneur’s token payouts. However, time inconsistency arises as the predetermined level of investment (optimal *ex ante*) can be deemed suboptimal *ex post* as the conflict of interest arises between the entrepreneur and platform users. Blockchain technology enables commitment to predetermined rules of investment and can thus add value by addressing time inconsistency. Our paper is among the first to show the value of commitment brought by blockchains.<sup>3</sup> That said, we recognize that in practice, blockchain commitment is far from perfect, and that is why it is important to consider both predetermined and discretionary token supply (our baseline case).<sup>4</sup>

We analyze tokens as monetary assets that facilitate transactions in a fully dynamic setting rather than tokens as dividend-paying assets and their difference from traditional securities (e.g., Gryglewicz et al., 2020). Our paper builds upon Cong et al. (2021) (henceforth CLW). While CLW assume a fixed token supply (standard in the literature), in this paper, we analyze the optimal token supply and explore new questions on the dynamics of platform investment and financing, the conflict of interest between the entrepreneur and users, and the role of blockchain technology in platform economics.

Next, we further elaborate on our model setup and mechanisms. Users hold tokens as a means of payment on the platform, enjoying convenience yield that increases in platform productivity. Intuitively, the more productive a platform is, the more activities (and transactions) it supports. To capture the network effect, a distinguishing feature of platform businesses, we allow the convenience yield to depend on the number of users. The user base evolves endogenously for two reasons. First, the stochastic growth of productivity directly affects adoption. Second, users’ expectations of future token price varies over time. An intertemporal complementarity amplifies the effects of productivity growth on user-base dynamics – when potential users expect productivity growth and more users to join in future, they expect token price to appreciate and thus have a stronger incentive to adopt now.

<sup>3</sup> In a dynamic system where a large player interacts with a group of small players, the small players respond to the large player’s discretionary action. As a result, the large player’s decision-making environment changes in response to her own action. The large player may obtain a higher value by forgoing discretion and committing to a plan. This mechanism lies behind studies on the commitment of monetary and fiscal policies (e.g., Fischer, 1980; Kydland and Prescott, 1980; Lucas and Stokey, 1983; Barro and Gordon, 1983; Ljungqvist and Sargent, 2018) and, more recently, optimal corporate capital structure (e.g., DeMarzo and He, 2021).

<sup>4</sup> While some platforms restrict the maximum of token supply, such caps are typically large, leaving the gradual release of token reserves under the discretion of platform designers. Moreover, platform designers are often entitled to a significant fraction of total allocation, through which they can influence token supply despite various vesting schemes. Appendix A illustrates the discretionary allocation with examples.

<sup>1</sup> Buying back and burning tokens means sending them to a public “eater address” from which they can never be retrieved because the address key is unobtainable. Practitioners often burn tokens to boost token price and reward token holders (e.g., Binance and Ripple).

<sup>2</sup> The platform network effect—the positive externality of one user’s adoption on other users—amplifies the demand growth in a mechanism that is reminiscent of the knowledge spillover effect in Romer (1986).

The platform's investment in productivity is financed by token issuances. Therefore, tokens not only enable users to transact with one another, but they also serve as financing instruments. The platform can increase token supply and pay tokens to a pool of contributors for their efforts and resources that improve productivity.<sup>5</sup> Because the contributors sell tokens to users who value the convenience yield and thus are the natural buyers, the amount of resources the platform can raise by issuing tokens depends on the token price. Token price is determined endogenously by the users' token demand and the platform's supply.

The entrepreneur's value is the present value of the tokens she is paid net the costs of token buybacks. In the Markov equilibrium, the entrepreneur's value is a function of the current platform productivity and token supply, which are the two state variables. The marginal value of productivity is positive, capturing the equilibrium dynamics of users' adoption and the valuation of the tokens. The marginal value of token supply is negative due to the downward pressure of supply on token price and the entrepreneur's token payout. In order to protect the continuation value (i.e., the present value of future token payout), the entrepreneur may even find it optimal to buy back tokens (through external financing) and burn them out of circulation.<sup>6</sup> In equilibrium, the entrepreneur receives token payout when token supply is low relative to platform productivity and buys back tokens when token supply is relatively high. Fig. 1 provides a summary of the circulation of tokens in our dynamic platform economy.<sup>7</sup>

A key friction in our model is that when buying back tokens, the entrepreneur has to raise costly external funds. While token buybacks occur occasionally, the associated financing cost propagates into a dynamic token issuance cost in every state of the world because every time more tokens are issued, the entrepreneur's expectation of costly future buyback changes accordingly. Specifically, the entrepreneur's cost of issuing one more token (i.e., the marginal decline of continuation value) is larger than the market price of tokens (i.e., the users' valuation of tokens). This wedge causes the platform to under-invest in productivity.

In our model, tokens are perfectly liquid. For example, newly issued tokens are not subject to discounts due to informational asymmetry. They are simply valued by the marginal user's indifference condition. Despite the perfect liquidity, tokens are not immune to financial frictions. The token issuance cost emerges because the entrepreneur's

optimal buyback relies on costly external funds. In other words, the optimal strategy of token management transmits the traditional costs of external financing into an endogenous cost of token issuance.

The dynamic token issuance cost implies a conflict of interest between the entrepreneur and users. Productivity enhancement paid with tokens benefits users via a higher convenience yield. But more tokens in circulation implies a higher likelihood of costly token buyback in the future. Therefore, while the entrepreneur bears the costs of future token buyback, the benefits of token-financed investment are shared with users. Admittedly, part of these benefits flow to the entrepreneur through a higher token price (and higher value of token payout), but the entrepreneur cannot seize all surplus from users. Users are heterogeneous in deriving convenience yield from tokens, so only the marginal user breaks even while those who derive more convenience yield enjoy a positive surplus.<sup>8</sup> Token overhang, which is underinvestment due to the surplus leakage to users, is a fundamental feature of token-based financing.

After characterizing the optimal token-management strategy (i.e., investment, payout, and buyback), we analyze the value of introducing blockchain technology in our setting. Blockchains distinguish themselves from traditional technologies in several aspects: immutable record keeping due to their time-stamping and linked-list data structure, smart contracting for automating and ensuring execution, and distributed design for easier monitoring and decentralized governance. These features enable the commitment of predetermined token-supply rules that, we show, are valuable in addressing the underinvestment problem.

Specifically, motivated by Ethereum, we consider a constant rate of token issuances that finance investment. We find that commitment mitigates the underinvestment problem by severing the state-by-state linkage between investment and the token issuance cost. While the increased amount of tokens issued for investment results in more frequent costly token buyback, the entrepreneur's value is higher than the case with discretionary token supply, because the token price is higher under faster trajectories of productivity and user-base growth. Previous studies of tokens assume predetermined rules of supply. In contrast, our analysis starts from the fully discretionary supply of tokens. By comparing the discretionary case with the predetermined case, we are able to identify the value added by commitment and to partly explain the popularity of blockchain technology among the platform businesses.

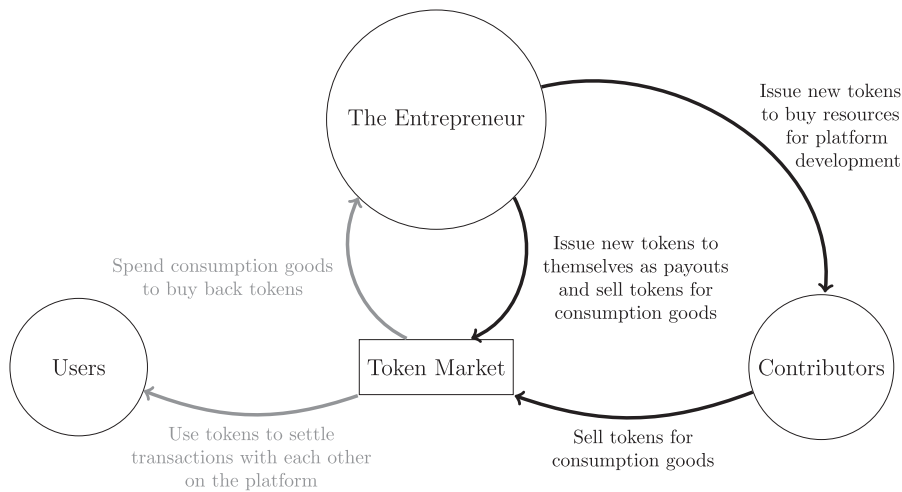
Finally, our model also has implications for the design of stablecoins. Different from the approaches based on collateralization, the entrepreneur in our setting supports the franchise value by occasionally buying back tokens out of circulation. The buyback happens when the token supply is high relative to the platform productivity – precisely at the moment that token price is low but the marginal value of reducing token supply is high. The resulting token

<sup>5</sup> Our focus on decentralized contributions is consistent with the vision of major token-based platforms that once the platform launches, the founding entrepreneurs' contributions tend to be limited relative to the decentralized contributors', such as KIN, a blockchain-based social network, and TON, a payment network.

<sup>6</sup> Burning tokens means sending them to a public "eater address" from which they can never be retrieved because the address key is unobtainable. Practitioners often burn tokens to boost token price and reward token holders (e.g., Binance and Ripple). Some also use Proof-of-Burn as an environmentally friendly alternative to Proof-of-Work to generate consensus (e.g., Counterparty (XCP) blockchain), or destroy unsold tokens or coins after an ICO or seasoned token issuances for fair play (e.g., Neblio's burning of NEBL tokens).

<sup>7</sup> We thank our discussant Sebastian Gryglewicz for sharing this figure with us in his discussion slides.

<sup>8</sup> The intuition is related to the surplus that a monopolistic producer forgoes to consumers when price discrimination is impossible. Here tokens are traded at a prevailing price among competitive users, so the entrepreneur cannot extract more value from users who derive a higher convenience yield from tokens.



**Fig. 1.** Token ecosystem. The black and gray arrows represent token supply and demand, respectively. We thank our discussant Sebastian Gryglewicz for sharing with us this figure in his discussion slides.

supply dynamics moderate the token price fluctuations. Therefore, for platforms with endogenous productivity growth, their tokens are inherently stable.

Overall, our model provides insight on the equilibrium dynamics of token-based communities and provides a guiding framework for practitioners. The various token offering schemes observed in practice can be viewed as special (suboptimal) cases. In Appendix A, we illustrate the institutional background and provide real-life examples.

The paper that is most related to ours is Gryglewicz et al. (2020), who also study endogenous platform productivity but focus on the founders' efforts, rather than decentralized contributors' efforts and resources. Mayer (2020) introduces speculators and studies the conflict of interest among various token holders. Our paper differs in our focus on tokens as a means of payment and on a different stage of platform life-cycle. Gryglewicz et al. (2020) model uncertainty in the exogenous arrival of platform launching and a constant token price post-launch. We study a post-launch platform with uncertainty from Brownian productivity shocks, and model the endogenous fluctuation of token price. Finally, while they consider a fixed token supply, we characterize the optimal state-contingent supply and highlight the value of commitment brought by blockchains.

Our paper connects the literature on platform economics to dynamic corporate finance, especially the studies emphasizing the role of financial slack and issuance costs (e.g., Bolton et al., 2011; Hugonnier et al., 2015; Décamps et al., 2016). Instead of cash management, we analyze platforms' token-supply management when investment induces user network effects and, importantly, the token price varies endogenously as users respond to supply variation.<sup>9</sup> From a methodological perspective, our paper is related to Brunnermeier and Sannikov (2016) and Li (2017), who both study the endogenous price determi-

nation of inside money (deposits) issued by banks. The key distinction is that tokens are outside money instead of liabilities of the platforms.

Our paper contributes to the broad literature on digital platforms. Studies on traditional platforms (e.g., Rochet and Tirole, 2003) do not consider the use of tokens as platforms' native currencies (local means of payment).<sup>10</sup> We share the view on platform tokens with Brunnermeier et al. (2019): a platform is a currency area where a unique set of economic activities take place and its tokens derive value by facilitating the associated transactions.<sup>11</sup> Beyond this, we emphasize that a platform can invest in its quality, for example, payment efficiency (Duffie, 2019), thereby raising token value. We are the first to formally analyze how platforms manage their investment and payout through token supply, and provide insights into the incentives and strategies of platform businesses.

Our paper adds to emerging studies on blockchains and cryptocurrencies (see Chen et al. (2020) for a review). We innovate upon CLW by endogenizing token supply and incorporating the entrepreneur's long-term interests (franchise value), which allows us to explore new issues concerning the dynamics of optimal platform investment and financing, the conflict of interest between the entrepreneur and users, and the role of blockchain technology in platform economics.<sup>12</sup> By doing so, we are able to provide the first unified theory of dynamic

<sup>10</sup> Stulz (2019) reviews the recent financial innovations by major digital platforms.

<sup>11</sup> Our model differs from the majority of monetary-policy models because token issuance finances investment, as in Bolton and Huang (2017), and payout rather than to stimulate nominal aggregate demand.

<sup>12</sup> The studies on the design issues of tokens (e.g., Proof-of-Work protocols) typically assume a fixed user base (e.g., Chiu and Wong, 2015; Chiu and Koepl, 2017). A fixed token supply is a common feature among the models that examine the roles of tokens among users and contributors (e.g., miners in Sockin and Xiong, 2018; Pagnotta, 2018) and the existing models of token valuation (e.g., Fanti et al., 2019).

<sup>9</sup> Related to Cagan (1956), the entrepreneur essentially maximizes the present value of seigniorage flows.

corporate finance of post-launch platforms: optimal monetary, investment, and payout policies with both token price and user base being endogenously determined. We also demonstrate the commitment value of blockchains.<sup>13</sup> Hinzen et al. (2019) show that limited adoption is an equilibrium outcome in Proof-of-Work (PoW) blockchains and Irresberger et al. (2019) empirically document that Proof-of-Stake (PoS) blockchains dominate in adoption scale. Our focus is on the use of tokens for platform finance and endogenous adoption, regardless of the consensus protocol and level of decentralization issues we explore in CLW.

Furthermore, our paper adds to the discussion on token price volatility and stablecoins. On the demand side, high token price volatility could be an inherent feature of platform tokens due to technology uncertainty and endogenous user adoption (see CLW).<sup>14</sup> Saleh (2018) emphasizes that token supply under Proof-of-Burn (PoB) protocols can reduce price volatility. We endogenize both the demand for tokens driven by users' transaction needs and dynamic adoption, and the supply of tokens for platform development and the founders' rent extraction. We show that the optimal token supply strategy stabilizes the token price.

Finally, our paper is broadly related to the literature on crowdsourcing and the gig economy. Blockchain-based consensus provisions in the form of cryptocurrency mining and resources (capital) raised via initial coin offerings (ICOs) are salient examples of decentralized on-demand contributions. Previous studies on ICOs and crowdfunding focus on one-time issuance of tokens before the platform launches (e.g., Canidio, 2018; Chod and Lyandres, 2018; Garratt and Van Oordt, 2019), yet platforms increase token supply on an on-going basis. Other studies center around the founders' hidden efforts or asymmetric information pre-launch, whereas we emphasize decentralized contributors' effort post-launch that is highly relevant for digital platforms and the gig economy.<sup>15</sup> This distinction is a key consideration in determining whether or not tokens are securities or not based on the Howey test.<sup>16</sup>

## 2. The model

In our model, three types of agents interact in a continuous-time economy: an entrepreneur (used inter-

<sup>13</sup> Even though commitments through tokens can be valuable in various settings (e.g., Goldstein et al., 2019), in practice, the reliability of blockchain and the associated commitment value are not free of costs (Abadi and Brunnermeier, 2018). As analyzed by Biais et al. (2019), Proof-of-Work protocols can lead to competing records of transactions ("forks"). Commitment is often implemented via smart contracts, for which Cong and He (2019) provide some examples.

<sup>14</sup> Hu et al. (2018) and Liu and Tsyvinski (2021) document token price dynamics empirically.

<sup>15</sup> The entrepreneurs in the ICO models do not engage in dynamic token management for long-term platform development, and thus, do not concern the franchise value. Despite newly issued tokens from platforms, decentralized contributors such as miners can also receive transaction fees (e.g., Basu et al., 2019; Easley et al., 2019; Huberman et al., 2019; Lehar and Parlour, 2020).

<sup>16</sup> For example, the SEC sued Telegram/TON that raised US\$1.7 billion through a private placement for not complying with securities laws (Michaels, 2019). The issue boils down to whether token investors post-launch expect to profit from the entrepreneurs' efforts or decentralized contributions.

changeably with "platform owners"), a pool of contributors, and a unit measure of users. The entrepreneur, representing the group of platform founders, key personnel, and venture investors, designs the platform's protocol. Contributors, who represent individual miners (transaction ledger keepers), third-party app developers, and other providers of on-demand labor in practice, devote efforts and resources required for the operation and continuing development of the platform. Users conduct peer-to-peer transactions and realize trade surpluses on the platform. A generic consumption good serves as the numeraire.

### 2.1. Platform productivity and contributors

We study a dynamically evolving platform whose productivity (synonymous with quality),  $A_t$ , evolves as follows:

$$\frac{dA_t}{A_t} = L_t dH_t, \quad (1)$$

where  $L_t$  is the decentralized contribution (contributors' resources and labor as described in Appendix A) the entrepreneur gathers through token payments to grow  $A_t$ .  $dH_t$  is an investment efficiency shock,

$$dH_t = \mu^H dt + \sigma^H dZ_t. \quad (2)$$

Here  $Z_t$  is a standard Brownian motion that generates the information filtration.<sup>17</sup>  $A_t$  broadly captures marketplace efficiencies, network security, processing capacity, regulatory conditions, users' interests, the variety of activities feasible on the platform, etc. It therefore directly affects users' utility on the platform, which is made clear below.

Our focus is on the dynamic interaction between the entrepreneur and users, so we do not explicitly model contributors' decision-making but instead specify directly the required numeraire value of compensation for  $L_t$  to be  $F(L_t, A_t)$ , which is increasing and convex in  $L_t$  and may also depend on  $A_t$ . Let  $P_t$  denote the unit price of the token in terms of the numeraire goods. Given  $A_t$ , to gather  $L_t$ , the platform needs to issue  $F(L_t, A_t)/P_t$  units of new tokens to workers, which adds to the total amount of circulating tokens,  $M_t$ .

A distinguishing feature of the labor supply in a "platform economy" or "gig economy" is that contributions are on-demand and contributors such as miners in Proof-of-Work-based public blockchains or ride-share drivers receive on-the-spot payments instead of long-term employment contracts. Tokens facilitate the acquisition of on-demand labor by avoiding the limited commitment on the part of the platform that arises in the implementation of deferred compensation, especially when workers and the platform belong to different judicial areas. Moreover, since digital tokens are often programmable (via smart contracting), escrow accounts can be set up and enforced automatically so that tokens are released to workers only if their inputs (e.g., programming codes or solutions to cryptography puzzles) are received. Therefore, tokens also reduce

<sup>17</sup> The process  $H_t$  may result from the entrepreneur's efforts prior to platform launch, which we take as exogenous to differentiate our model from models on founders' efforts as discussed in the literature review.



the platform’s exposure to workers’ limited commitment.<sup>18</sup> Finally,  $L_t$  can also include the capital received from crowd-based investors. Investors receive tokens immediately, instead of receiving contracts for future payments.

When the platform is token-based, the concern of dilution naturally arises – workers and investors’ tokens may depreciate if the platform issues more tokens in the future. In other words, while tokens avoid limited commitments by facilitating spot payments, the platform’s lack of commitment against increasing the token supply is still a concern. To see how our analysis of optimal token supply addresses this question, we first introduce platform users.

### 2.2. Platform users

As in CLW, users can conduct transactions by holding tokens. We use  $x_{i,t}$  to denote the value (real balance) of agent  $i$ ’s holdings in units of numeraires. By facilitating transactions, these holdings generate a flow of utility (or convenience yield) over  $dt$  given by:

$$x_{i,t}^{1-\alpha} (N_t^\gamma A_t u_i)^\alpha dt, \tag{3}$$

where  $N_t$  is the platform user base,  $u_i$  captures agent  $i$ ’s needs for platform transactions, and  $\alpha, \gamma \in (0, 1)$  are constants. Similar to CLW, we provide a theoretical foundation in Appendix B. A crucial difference from CLW is that we endogenize  $A_t$  and the token supply  $M_t$ .

The flow utility of token holdings depends on  $N_t$ , the total measure of users on the platform with  $x_{i,t} > 0$ .<sup>19</sup> This specification captures the network externality among users, such as the greater ease of finding trading or contracting counterparties in a larger community.

We allow users’ transaction needs,  $u_i$ , to be heterogeneous. Let  $G_t(u)$  and  $g_t(u)$  denote the cross-sectional cumulative distribution and density function respectively that are continuously differentiable over a positive support  $[\underline{u}_t, \bar{u}_t]$ .  $u_i$  can be broadly interpreted: For payment blockchains (e.g., Ripple and Bitcoin), a high value of  $u_i$  reflects user  $i$ ’s needs for international remittance. For smart-contracting platforms (e.g., Ethereum),  $u_i$  captures user  $i$ ’s project productivity, and token holdings facilitate contracting.<sup>20</sup> In decentralized computation (e.g., Dfinity

and data storage (e.g., Filecoin) applications,  $u_i$  corresponds to the need for secure and fast access to computing power and data.

Recall that  $P_t$  denotes the unit price of a token in terms of the numeraire. Let  $k_{i,t}$  denote the number of tokens that user  $i$  holds, then the real balance is:

$$x_{i,t} = P_t k_{i,t}. \tag{4}$$

To join the platform (i.e.,  $k_{i,t} > 0$ ), a user incurs a flow cost  $\phi dt$ . For example, transacting on the platform requires attention; account maintenance and data migration also take effort. Therefore, only agents with sufficiently high  $u_i$  choose to join the platform.

Let  $y_{i,t}$  denote user  $i$ ’s cumulative utility from platform activities. We follow CLW and assume that the users are well-diversified so that their transaction surpluses and financial gains on the platform are priced by an exogenous stochastic discount factor. Thus, we can interpret the equilibrium dynamics as dynamics under the risk-neutral measure. When users are risk neutral, the risk-neutral measure coincides with the data-generating probability (physical measure). User  $i$ ’s objective is given by:

$$\mathbb{E} \left[ \int_0^\infty e^{-rt} dy_{i,t} \right], \tag{5}$$

where the incremental utility  $dy_{i,t}$  is:

$$dy_{i,t} = \max \left\{ 0, \max_{k_{i,t} > 0} \left[ (P_t k_{i,t})^{1-\alpha} (N_t^\gamma A_t u_i)^\alpha dt + k_{i,t} \mathbb{E}_t [dP_t] - \phi dt - P_t k_{i,t} r dt \right] \right\}. \tag{6}$$

The outer “max” operator in Eq. (6) reflects user  $i$ ’s option to leave and obtain zero surplus from platform activities, and the inner “max” operator reflects user  $i$ ’s optimal choice of  $k_{i,t}$ . Inside the inner max operator are four terms that give the incremental transaction surpluses from platform activities. The first corresponds to the payment convenience yield given in Eq. (3). The second is the expected capital gains from holding  $k_{i,t}$  units of tokens. The third is the participation cost and the last term is the financing) cost of holding  $k_{i,t}$  units of tokens.

It is worth emphasizing that platform users must hold tokens for at least an instant,  $dt$ , to complete transactions and derive utility flows, and are therefore exposed to a token price change over  $dt$ . Appendix A contains motivating examples and institutional details. We implicitly assume a liquid secondary market for tokens. Hence, after receiving tokens, decentralized contributors can immediately sell tokens to users. Contributors can also be users themselves, and the model is not changed as long as the utility from token usage and the disutility from contributing  $L_t$  (which gives rise to  $F(\cdot)$ ) are additively separable.

### 2.3. The entrepreneur

We collectively refer to the founding entrepreneurs, the key developers, and initial investors who own the platform as the entrepreneur. Importantly, the entrepreneur designs the platform protocols and determines the investment strategies  $\{L_t, t \geq 0\}$ . Over time, the entrepreneur receives

<sup>18</sup> Another reason to introduce tokens as a means of payment for  $L_t$  is the heterogeneity in labor quality. Consider a subset of workers who supply high-quality efforts because they better understand the technologies behind the platform. Naturally, these capable workers assign a higher value to tokens because they are not concerned about the adverse selection problem that low-quality workers face due to their lack of technological knowledge. In other words, in contrast to cash-based compensation, token-based compensation screens out high-type workers and thereby improves the match between the employer (platform) and employees (workers).

<sup>19</sup> One example involves a producer who accepts tokens as a means of payment and earns net profits equal to the full transaction surplus. The profits depend on the scale of operation, i.e., the sales  $x_{i,t}$ , and variables that determine the profit margin, which include the total customer outreach,  $N_t$ , the platform efficiency  $A_t$ , and the producer’s idiosyncratic productivity  $u_i$ .

<sup>20</sup> For example, in a debt contract, the borrower’s Ethereum can be held in an escrow or “margin” account, which is automatically transferred to the lender in case of default. Posting more Ethereum as margin allows for larger debt contracts, which in turn lead to projects of larger scale and profits.

a cumulative number of tokens  $D_t$  as dividends and, similar to users, evaluates the tokens with a risk-neutral objective function and discount rate  $r$ :

$$\max_{\{L_t, D_t\}_{t \geq 0}} \int_0^{+\infty} \mathbb{E} \left[ e^{-rt} P_t dD_t \left[ \mathbb{I}_{\{dD_t \geq 0\}} + (1 + \chi) \mathbb{I}_{\{dD_t < 0\}} \right] \right]. \quad (7)$$

When  $dD_t > 0$ , the entrepreneur receives token dividends that have a market value  $P_t$  per unit, as a form of compensation for his essential human capital.<sup>21</sup> Note that token dividends can be either continuous (i.e., of  $dt$  order) or lumpy, and that in equilibrium, the entrepreneur immediately sells her tokens to users who are the natural buyers of tokens because they derive an extra convenience yield from token holdings.

We allow the entrepreneur to buy back and burn tokens to reduce the token supply (i.e.,  $dD_t < 0$ ). When  $dD_t < 0$ , the entrepreneur raises external financing (numeraire goods) at a proportional cost  $\chi$  for token buyback.<sup>22</sup> By reducing token supply, the entrepreneur can boost token price, and consequently increase the value of future token dividends. A higher token price also allows the platform to gather more resources for productivity growth. We allow the amount of token buyback to be continuous (i.e., of  $dt$  order) or lumpy.

The key accounting identity that describes the evolution of token supply entails both the tokens issued to finance platform investment and the entrepreneur's dividend/buyback:

$$dM_t = \frac{F(L_t, A_t)}{P_t} dt + dD_t. \quad (8)$$

When the platform invests (the first term on the right-hand side) or distributes token dividends ( $dD_t > 0$ ), the total amount of tokens in circulation increases; the token supply decreases when the entrepreneur burns tokens out of circulation ( $dD_t < 0$ ).<sup>23</sup> In the next section, we show that the entrepreneur's financial slack decreases in  $M_t$ . An increase in  $M_t$  depresses token price  $P_t$ , so when  $M_t$  rises to a sufficiently high level, the entrepreneur, who is concerned over the value of future token payouts (i.e., the continuation value), pays the financing cost to raise funds for token buyback that token price. Therefore, under the financing cost  $\chi$ , managing the token stock is akin to managing cash inventory, as in Bolton et al. (2011) and Hugonnier et al. (2015). A firm's financial slack increases in

its cash holdings, because when its cash dries up, the firm has to resort to costly external funds. In our model, the financial slack decreases in token supply, because when the token supply rises too high, the entrepreneur has to buy back tokens with costly external funds.

In Definition 1, we characterize a Markov equilibrium. The two state variables are the productivity  $A_t$ , which measures the technological aspect of the platform, and the token supply  $M_t$ , which inversely measures the financial slack.

*Definition 1.* A Markov equilibrium with state variables  $A_t$  and  $M_t$  is comprised of agents' decisions and token price dynamics, such that the token market-clearing condition holds, users optimally decide to participate (or not) and choose token holdings, contributors supply resources for the compensation of  $F(L_t, A_t)$  in numeraire value, and the platform strategies, i.e.,  $L_t$  and  $D_t$ , are optimally designed to maximize the entrepreneur's value.

### 3. Dynamic equilibrium

We first derive the entrepreneur's optimal investment and token payout and buyback, which in turn pin down the token supply. We then derive platform users' optimal decisions on adoption and token holding in order to aggregate token demand. Finally, token market clearing yields the equilibrium dynamics of token price.

#### 3.1. Optimal token supply

At time  $t$ , the entrepreneur's continuation or franchise value  $V_t$  (i.e., the time- $t$  value function) satisfies the following Hamilton–Jacobi–Bellman (HJB) equation:

$$\begin{aligned} rV(M_t, A_t)dt = & \max_{L_t, D_t} P_t dD_t \left[ \mathbb{I}_{\{dD_t \geq 0\}} + (1 + \chi) \mathbb{I}_{\{dD_t < 0\}} \right] \\ & + V_{M_t} \left[ \frac{F(L_t, A_t)}{P_t} dt + dD_t \right] \\ & + V_{A_t} A_t L_t \mu^H dt + \frac{1}{2} V_{A_t A_t} A_t^2 L_t^2 (\sigma^H)^2 dt. \quad (9) \end{aligned}$$

The first term in this HJB equation reflects the dividend payout ( $dD_t > 0$ ) and buyback ( $dD_t < 0$ ). When there are more tokens in circulation, the token price is depressed and the entrepreneur's continuation value is reduced. Therefore, we expect  $V_{M_t} < 0$ , which we later confirm in the numerical solution. Payout occurs only if  $-V_{M_t} \leq P_t$ , i.e., the market value of token weakly exceeds the marginal cost of increasing token supply. Token buyback happens when  $-V_{M_t} \geq P_t(1 + \chi)$ , i.e., the marginal benefit of decreasing token supply is not lower than the cost of burning tokens. The second term is the product of the marginal value of token supply,  $V_{M_t}$ , and the drift of token supply, which consists of tokens paid to contributors and tokens distributed to or burned by the entrepreneur. The third term is the marginal benefit of an increase in  $A_t$ . The productivity increases in  $L_t$ , but obtaining  $L_t$  with token payments increases the token supply  $M_t$ , which has a marginal cost of  $V_{M_t} \frac{F_{L_t}}{P_t} dt$ . Moreover, investment outcome is uncertain, so the fourth term captures how such risk

<sup>21</sup> For example, blockchain behemoth Bitmain Technologies Ltd. and Founders Fund (known for early bets on SpaceX and Airbnb) invest in EOS and hold ownership stakes that entitle them to future token rewards. The gradual distribution of token dividends can be viewed as contingent vesting in reality – a certain amount of total tokens  $D_t$  have been allocated by time  $t$  but are distributed over time (via  $dD_t$ ) depending on the stages of platform development and the tokens outstanding (i.e., different values of  $A_t$  and  $M_t$ ).

<sup>22</sup> The external financing cost assumption (via parameter  $\chi$ ) is in line with those in the corporate finance literature, e.g., Bolton et al. (2011) and Hugonnier et al. (2015), who model in reduced form the information, incentive, and transactions costs of raising external funds.

<sup>23</sup> It is suboptimal for the platform to pay contributors with costly external financing. Instead, it is generally optimal to use tokens (internal financing) to compensate contributors as doing so delays incurring the costs of external financing. However, using tokens as internal funds incurs a shadow cost because an increase in token supply depresses token price, which reduces the entrepreneur's token payout value.

enters into the choice of  $L_t$ . We summarize the optimal policies in Proposition 1

*Proposition 1 (Optimal Token Supply).* The optimal  $L_t$  is solved implicitly as a function of state variables,  $A_t$  and  $M_t$ , by:

$$V_{A_t} A_t \mu^H + V_{A_t A_t} A_t^2 L_t^* (\sigma^H)^2 = F_L(L_t^*, A_t) \left( \frac{-V_{M_t}}{P_t} \right). \quad (10)$$

The optimal  $dD_t$  is characterized as follows: the entrepreneur receives token payouts ( $dD_t^* > 0$ ) when  $P_t \geq -V_{M_t}$ , and buys back and burns tokens ( $dD_t^* < 0$ ) when  $-V_{M_t} \geq P_t(1 + \chi)$ .

In Eq. (10), we equate the marginal benefit of investment to the marginal cost. The left-hand side is the marginal impact on the drift of  $A_t$ , evaluated by the entrepreneur’s marginal value of  $A_t$  growth and adjusted for the risk of productivity shock via the second term. The right-hand side is the marginal cost of investment. Since the entrepreneur’s marginal cost of token supply can be larger than the market value of tokens, the physical marginal cost  $F_L$  is multiplied by  $-V_{M_t}/P_t$ . This multiplier reflects a token issuance cost. Here the platform pays for investment with “undervalued” tokens. The payout/buyback policy in Proposition 1 implies that  $-V_{M_t}/P_t \in [1, 1 + \chi]$ . Because the entrepreneur incurs a financing cost  $\chi > 0$  when burning tokens, there exists a region of  $(M_t, A_t)$  such that  $V_{M_t}/P_t > 1$ , which reflects the cost of issuing tokens. A corollary from Proposition 1 highlights the link between off-platform capital-market frictions and the platform’s token issuance cost:

*Corollary 1 (Token Issuance Cost).* The financing cost  $\chi > 0$  leads to a token issuance cost for the entrepreneur (i.e.,  $-V_{M_t}/P_t > 1$  for a positive measure of  $(M_t, A_t)$ ). The issuance cost distorts the investment policy by amplifying the marginal cost of investment in Eq. (10).

Token issuance cost arises even though the token market is perfectly liquid. The financing cost creates a conflict of interest between the insider (the entrepreneur) and outsiders (users). A productivity enhancement paid with new tokens benefits users via a higher convenience yield. But more tokens in circulation implies a higher likelihood of token buyback and incidence of financing cost in the future for the entrepreneur. While the entrepreneur bears the financing cost, the benefits are shared with users. Admittedly, as the token demand strengthens following a productivity increase, the entrepreneur benefits from a higher token price (and higher value of token payout), but the entrepreneur cannot capture the full surplus.

Users are heterogeneous in deriving convenience yield from tokens, so only the marginal user breaks even after token price increases, while those who derive more convenience yield capture a positive surplus. The intuition is similar to that in a monopolistic producer’s problem when full price discrimination is impossible. Here tokens are traded at a prevailing price among competitive users, so the entrepreneur cannot extract more value from users who derive a higher convenience yield than the marginal token holder.

As such, token-based financing naturally exhibits token overhang, which is underinvestment due to the leakage of

surplus to users. Uncertainty also plays a critical role here. Without  $dZ_t$ , the productivity shock,  $L_t$ , always increases  $A_t$ . Then, with a sufficiently efficient investment technology  $F(\cdot)$  (so that relatively few new tokens are needed to pay for  $L_t$ ), we arrive at a situation where, following investment,  $A_t$  always grows faster than  $M_t$ . As we will show below, the entrepreneur conducts costly token buyback when  $M_t$  is too high relative to  $A_t$ . Thus, with  $A_t$  always growing faster than  $M_t$ , the entrepreneur always moves away from costly token buyback after making an investment. As a result, the financing cost is never a concern given this sufficiently efficient  $F(\cdot)$ . However, in the presence of uncertainty in investment outcome, there always exists a probability that  $M_t$  increases faster than  $A_t$  after investment, moving the platform closer to costly buyback.

In sum, the mechanism of token overhang relies on three ingredients in the model. First, when the entrepreneur raises consumption goods to buy tokens out of circulation, the entrepreneur faces a financing cost. Second, users are heterogeneous in deriving convenience yield from token holdings, so under a single token price that clears the competitive market, only the marginal user breaks even. Third, the outcome of platform investment is uncertain. The first ingredient creates a private cost of investment for the entrepreneur, and the second implies a surplus leakage to users. Together, they generate a conflict of interest between the entrepreneur and users. Finally, the third ingredient, uncertainty, is needed so that despite the specification of  $F(\cdot)$ , token overhang always exists.

Our characterization of the optimal investment and payout/buyback policies in some sense allays the concern over fraudulent designs or manipulations by the founding developers, for example, through building “back doors” in the protocol to steal tokens and depress the token price when selling the stolen tokens in secondary markets. As shown in Proposition 1, our setup allows the entrepreneur to extract tokens as dividends, and the optimal payout policy already maximizes the entrepreneur’s value. In other words, the policy is incentive-compatible in this subgame perfect equilibrium between a large player (the entrepreneur) and a continuum of small players (users). From a regulatory perspective, a proposal of blockchain or platform design should disclose the policy of token payout to the platform owners, and it should be broadly in line with the above characterization.

### 3.2. Aggregate token demand

We conjecture and later verify that in equilibrium, the token price,  $P_t$ , evolves as

$$dP_t = P_t \mu_t^P dt + P_t \sigma_t^P dZ_t, \quad (11)$$

where  $\mu_t^P$  and  $\sigma_t^P$  are endogenously determined. Agents take the price process as given under rational expectation. Conditioning on joining the platform, user  $i$  chooses the optimal token holdings,  $k_{i,t}^*$ , by using the following first-order condition,

$$(1 - \alpha) \left( \frac{N_t^\gamma A_t u_i}{P_t k_{i,t}^*} \right)^\alpha + \mu_t^P = r, \quad (12)$$



which states that the sum of marginal transaction surplus on the platform and the expected token price change is equal to the required rate of return,  $r$ .

Rearranging this equation, we obtain the following expression for optimal token holdings:

$$k_{i,t}^* = \frac{N_t^\gamma A_t u_i}{P_t} \left( \frac{1 - \alpha}{r - \mu_t^p} \right)^{\frac{1}{\alpha}}. \tag{13}$$

$k_{i,t}^*$  has several properties. First, users hold more tokens when the common productivity,  $A_t$ , or user-specific transaction need,  $u_i$ , is high, and also when the user base,  $N_t$ , is larger due to network effects. Eq. (13) reflects an investment motive to hold tokens, that is  $k_{i,t}^*$  increases in the expected token appreciation,  $\mu_t^p$ .

Using  $k_{i,t}^*$ , we obtain the following expression for the user's maximized profits conditional on participating on the platform:

$$N_t^\gamma A_t u_i \alpha \left( \frac{1 - \alpha}{r - \mu_t^p} \right)^{\frac{1-\alpha}{\alpha}} - \phi. \tag{14}$$

User  $i$  only participates when the preceding expression is non-negative. That is, only those users with sufficiently large  $u_i$  participate. Let  $\underline{u}_t$  denote the type of the marginal user, then

$$\underline{u}_t = \underline{u}(N_t; A_t, \mu_t^p) = \frac{\phi}{N_t^\gamma A_t \alpha} \left( \frac{r - \mu_t^p}{1 - \alpha} \right)^{\frac{1-\alpha}{\alpha}}. \tag{15}$$

The adoption threshold  $\underline{u}_t$  decreases in  $A_t$  because a more productive platform attracts more users. The threshold also decreases when users expect a higher token price appreciation (i.e., higher  $\mu_t^p$ ). Because only agents with  $u_i \geq \underline{u}_t$  participate, the user base is then:

$$N_t = 1 - G_t(\underline{u}_t). \tag{16}$$

Eqs. (15) and (16) jointly determine the user base  $N_t$  given  $A_t$  and  $\mu_t^p$ .<sup>24</sup>

*Proposition 2 (Token Demand and User Base). Given  $A_t$  and  $\mu_t^p$ , the platform has a positive user base when Eqs. (15) and (16) have solutions for  $\underline{u}_t$  and  $N_t$ . Conditional on participating, user  $i$ 's optimal token holding,  $k_{i,t}^*$ , is given by Eq. (13). The token holding,  $k_{i,t}^*$ , decreases in  $P_t$  and increases in  $A_t$ ,  $\mu_t^p$ ,  $u_i$ , and  $N_t$ .*

### 3.3. Token market clearing

Clearing the token market pins down the token price. We define the participants' aggregate transaction need by aggregating  $u_i$  of participating users:

$$U_t := \int_{u \geq \underline{u}_t} u g_t(u) du. \tag{17}$$

The market-clearing condition is:

$$M_t = \int_{i \in [0,1]} k_{i,t}^* di. \tag{18}$$

<sup>24</sup> We do not consider the trivial solution of zero adoption, which always leads to a zero token price.

Substituting optimal holdings in Eq. (13) into the market-clearing condition in Eq. (18), we arrive at the token pricing formula in Proposition 3.

*Proposition 3 (Token Pricing). The equilibrium token price is given by*

$$P_t = \frac{N_t^\gamma U_t A_t}{M_t} \left( \frac{1 - \alpha}{r - \mu_t^p} \right)^{\frac{1}{\alpha}}. \tag{19}$$

Token price increases in  $N_t$ . The larger the user base, the higher the trade surplus individual participants can realize by holding tokens, and the stronger the token demand. The price-to-user base ratio increases in the productivity, the expected price appreciation, and the network participants' aggregate transaction need, while it decreases in the token supply  $M_t$ .<sup>25</sup> Eq. (19) implies a differential equation for  $P_t$  in the state space of  $(M_t, A_t)$ . This can be clearly seen once we apply the infinitesimal generator to  $P_t = P(M_t, A_t)$ , expressing  $\mu_t^p$  into a collection of first and second derivatives of  $P_t$  by Itô's lemma. Note that the equilibrium user base,  $N_t$ , is already a function of  $A_t$  and  $\mu_t^p$ , as shown in Proposition (2). Therefore, the collection of token market-clearing conditions at every  $t$  essentially characterize the full dynamics of token price. This method of solving token price follows CLW.

Eqs. (8) and (18) describe the primary and secondary token markets. The change of  $M_t$  is a flow variable, given by Eq. (8), that includes the new issuances from platform investment and payout and the repurchases by the entrepreneur. The token supply  $M_t$  is a stock variable, and through Eq. (18), it equals the token demand of users.

The problem faced by a token-based platform is reminiscent of a durable-good monopoly problem (e.g., Coase, 1972; Stokey, 1981; Bulow, 1982). First, token issuance permanently increases the supply. When issuing tokens to finance investment or payout, the entrepreneur is competing with future selves. Second, given a zero physical cost of creating tokens, the Coase intuition seems applicable: The entrepreneur can be tempted to satisfy the residual demand by ever lowering token price as long as the price is positive (i.e., above the marginal cost of production). Thus, users wait for lower prices, driving the token price to zero. Our model differs from the Coasian setting in two aspects. First, even though the physical cost of producing tokens is zero, the dynamic token issuance cost increases in the token supply as we show in the next section. This is reminiscent of the result in Kahn (1986) that the Coase intuition does not hold in the presence of increasing marginal cost of production. Second, in contrast to theories of durable-good monopoly, token demand in our model is not stationary; in fact, it increases geometrically with the endogenously growing  $A_t$ , so users cannot expect a

<sup>25</sup> The formula reflects certain observations by practitioners, such as incorporating DAA (daily active addresses) and NVT ratio (market cap to daily transaction volume) into token valuation framework, but instead of heuristically aggregating such inputs into a pricing formula, we solve both token pricing and user adoption as an equilibrium outcome. See, for example, *Today's Crypto Asset Valuation Frameworks* by Ashley Lannquist at Blockchain at Berkeley and Haas FinTech.

lower token price in the future. Therefore, we can solve an equilibrium with a positive token price in the next section.

#### 4. Equilibrium characterization

We further characterize the equilibrium by analytically deriving and numerically solving the system of differential equations concerning token price and the entrepreneur’s value function. To streamline exposition and focus on core economic insights, we make some intuitive parametric assumptions.

##### 4.1. User distribution and investment cost function

We assume that  $u_i$  follows the commonly used Pareto distribution on  $[\underline{U}_t, +\infty)$  with cumulative probability function (c.d.f.) given by the Pareto distribution:

$$G_t(u) = 1 - \left(\frac{\underline{U}_t}{u}\right)^\xi, \tag{20}$$

where  $\xi > 1$  and  $\underline{U}_t = 1/(\omega A_t^\kappa)$ ,  $\omega > 0$ , and  $\kappa \in [0, 1]$ . The cross-section mean of  $u_i$  is  $\frac{\xi \underline{U}_t}{\xi - 1}$ . It is assumed that  $\underline{U}_t$  decreases in  $A_t$ , which reflects the competition from follower platforms inspired by the success (high  $A_t$ ) of the platform in question. For example, after the success of Bitcoin, alternative blockchains emerge as competitors in the area of payments. Similarly, there are alternative platforms to Ethereum for smart contracting. The overall effects of competition depend on the parameters  $\omega$  and  $\kappa$ , while the parameter  $\xi$  governs how heterogeneous users transaction needs ( $u_i$ ) are (i.e., the dispersion of  $u_i$  distribution). Appendix D provides comparative statics of these parameters.

*Lemma 1 (Parameterized User Base).* Given  $A_t$  and  $\mu_t^P$ , from Proposition 2, we have a unique non-degenerate solution,  $N_t$ , from Eqs. (15) and (16), given by:

$$N_t = A_t' \left(\frac{\alpha}{\omega \phi}\right)^{\frac{\xi}{1-\xi\gamma}} \left(\frac{1-\alpha}{r-\mu_t^P}\right)^{\left(\frac{\xi}{1-\xi\gamma}\right)\left(\frac{1-\alpha}{\alpha}\right)},$$

where  $A_t' \equiv A_t^{(1-\kappa)\left(\frac{\xi}{1-\xi\gamma}\right)}$ , (21)

if  $\underline{u}_t \geq \frac{1}{\omega A_t^\kappa}$ , i.e.,  $A_t^{1-\kappa} \left(\frac{1-\alpha}{r-\mu_t^P}\right)^{\frac{1-\alpha}{\alpha}} \leq \frac{\omega \phi}{\alpha}$ ; otherwise,  $N_t = 1$ .

$A_t'$  is a transformed version of  $A_t$ . It is the effective productivity that captures user homogeneity, platform competition, and user network effects. Intuitively, the way productivity matters is amplified by the network-effect parameter  $\gamma$  (introduced in Eq. (3)) but dampened by the competition parameter  $\kappa$ . When there is no network effect ( $\gamma = 0$ ) or competition ( $\kappa = 0$ ), the exponent is simply  $\xi$ , which measures user heterogeneity. The effect of user heterogeneity has two components. One is the interaction component with  $\gamma$ , as seen in the denominator of  $\frac{\xi}{1-\xi\gamma}$ . When agents are more homogeneous (larger  $\xi$ ), small changes in  $A_t$  brings big changes in adoption, which is amplified by network effects. The second component is in the numerator of  $\frac{\xi}{1-\xi\gamma}$ . Even without the network effect, greater homogeneity still means that there is a bigger adoption sensitivity with respect to platform productivity.

Our later discussion focuses on  $\xi\gamma < 1$ , so that the user base,  $N_t$ , increases in the platform productivity despite platform competition. This is realistic because a technology leader usually benefits from its innovation despite the presence of competing followers. Moreover, we focus on low values of  $A_t$ , such that  $N_t < 1$  in the Markov equilibrium so as to examine how token allocation interacts with user base dynamics. Under the Pareto distribution, the aggregate transaction need is given by:

$$U_t = N_t \left(\frac{\xi \underline{U}_t}{\xi - 1}\right). \tag{22}$$

*Lemma 2 (Parameterized Token Price).* The equilibrium token price in Proposition 3 when  $N_t < 1$  is given by:

$$P_t = \frac{A_t'}{M_t} \frac{\xi}{(\xi - 1)\omega^{\frac{\xi}{1-\xi\gamma}}} \left(\frac{\alpha}{\phi}\right)^{\frac{\xi}{1-\xi\gamma}-1} \left(\frac{1-\alpha}{r-\mu_t^P}\right)^{1+\left(\frac{\xi}{1-\xi\gamma}\right)\left(\frac{1-\alpha}{\alpha}\right)}. \tag{23}$$

Next, we follow previous studies on investment in finance and macroeconomics (e.g., Hayashi, 1982) to specify a convex (quadratic) investment cost function:

$$F(L_t, A_t) = \left(L_t + \frac{\theta}{2} L_t^2\right) A_t', \tag{24}$$

and  $\theta \geq 0$  can depend on the elasticity of contributors’ resource supply. The particular functional form ensures analytical tractability because  $F(L_t, A_t)$  being linear in  $A_t'$  not only captures the reality that contribution compensation depends on the effective productivity of the platform, but also allows us to reduce the dimensionality of the state variables when solving the model. The specification also allows us to characterize optimality via the first-order condition for investment, similar to the F.O.Cs in Hayashi-style q-theoretic models with convex adjustment costs. In general, the investment cost is higher when the platform is more productive because incremental improvements in the productivity become harder (note that  $L_t$  enters into the growth rate of  $A_t$ ). It is quadratic in the decentralized contribution the entrepreneur gathers to reflect the increasing marginal cost of adding  $L_t$ .<sup>26</sup> For example, to induce more miners to mine Bitcoin, more rewards must be given as miners’ competition drives up their cost of mining through higher electricity prices.

We characterize a Markov equilibrium in a transformed state space. The equilibrium variables depend on  $(m_t, A_t)$ , where the productivity-normalized token supply is given by:

$$m_t = \frac{M_t}{A_t'}. \tag{25}$$

<sup>26</sup> While we view this as a reasonable starting point, we are fully aware that the implicit adjustment costs for labor or capital may not be convex. Investment may be lumpy and fixed costs can be important in reality. In corporate finance, Hugonnier et al. (2015) show that lumpy investment for a financially constrained firm facing costly external equity issuance generates different investment and financing dynamics from those in a model based on smooth investment adjustment costs, for example, Bolton et al. (2011). For example, Hugonnier et al. (2015) show that the value function may not be globally concave and smooth pasting conditions may not guarantee optimality.

By inspecting Eq. (23), we can see that  $m_t$  is the only state variable driving the token price. By Itô's lemma,  $\mu_t^P$  is a function of  $m_t$  if and only if  $P_t$  is a function of  $m_t$ .

Moreover, the entrepreneur's value function exhibits a homogeneity property,  $V(M_t, A_t) = v(m_t)A_t'$ . These properties significantly simplify our analysis. In the interior region where  $dD_t = 0$ , denoting  $(1 - \kappa)(\frac{\xi}{1 - \xi\gamma})$  by  $\delta$ , we simplify the HJB Eq. (9) under  $V_t = v(m_t)A_t'$  to an ordinary differential equation for  $v(m_t)$ , as follows:

$$rv(m_t) = \max_{L_t} v'(m_t) \frac{(L_t + \frac{\theta}{2}L_t^2)}{P_t} + [v(m_t) - v'(m_t)m_t] \times \left[ \delta\mu^H L_t + \frac{1}{2}\delta(\delta - 1)(\sigma^H)^2 L_t^2 \right] + \frac{1}{2}v''(m_t)m_t^2\delta^2(\sigma^H)^2 L_t^2. \tag{26}$$

Under the specification of  $F(\cdot)$  in Eq. (24), the HJB equation implies the following optimal investment via the standard first-order condition.

*Lemma 3 (Parameterized Optimal Investment).* Under the specification of investment cost function,  $F(\cdot)$ , in Eq. (24), the optimal investment is given by:

$$L_t^* = \frac{[v(m_t) - v'(m_t)m_t]\delta\mu^H + \frac{v'(m_t)}{P_t}}{-\frac{v'(m_t)}{P_t}\theta - v''(m_t)m_t^2\delta^2(\sigma^H)^2 - \delta(\delta - 1)(\sigma^H)^2[v(m_t) - v'(m_t)m_t]}. \tag{27}$$

The optimality conditions for  $dD_t$  give us the boundary conditions for solving  $v(m_t)$  and  $P(m_t)$ . The marginal value of retained tokens must be equal to the market value,

$$-v'(\underline{m}) = P(\underline{m}), \tag{28}$$

at the optimal payout boundary,  $\underline{m}$ , and we have the standard “super contact” condition:

$$-v''(\underline{m}) = P'(\underline{m}). \tag{29}$$

As the payout boundary is a reflecting boundary, to rule out arbitrage in the token market, we have:

$$P'(\underline{m}) = 0. \tag{30}$$

Intuitively, the distribution of token dividends happens when the token supply is sufficiently small relative to the platform productivity, i.e., low  $m_t$ . Similarly, at the buyback boundary, denoted by  $\bar{m}$ , we have the following conditions:

$$-v'(\bar{m}) = P(\bar{m})(1 + \chi); \tag{31}$$

$$-v''(\bar{m}) = P'(\bar{m})(1 + \chi); \tag{32}$$

$$P'(\bar{m}) = 0. \tag{33}$$

The optimal amounts of token payout or buyback are determined as follows. The payout boundary,  $\underline{m}$ , is a reflecting boundary of  $m_t = M_t/A_t'$ . When  $m_t = \underline{m}$ , any decrease of  $m_t$  (e.g., due to a positive shock to  $A_t'$ ) leads to payout, and the payout amount is precisely equal to the increase in  $M_t$  (the numerator) that is required to bring  $m_t$  back up to  $\underline{m}$ . Similarly, at the buyback boundary,  $\bar{m}$ , is also a reflecting boundary of  $m_t$ . At  $\bar{m}$ , any increase of  $m_t$  (e.g., due to a negative shock to  $A_t'$ ) leads to token

buyback, and the buyback amount is equal to the decrease in  $M_t$  that is required to bring  $m_t$  back down to  $\bar{m}$ .

*Proposition 4 (Solving the Markov Equilibrium).* With Lemmas 1, 2, and 3, there exists a Markov equilibrium with  $A_t$  (equivalently  $A_t'$ ) and  $m_t = M_t/A_t'$  as the state variables, and the equilibrium has the following properties:

(i)  $P(m_t)$  and  $v(m_t)$  uniquely solve the system of ordinary differential equations given by Eqs. (23) and (26) subject to boundary conditions given by Eqs. (28) to (33).

(ii) The entrepreneur's optimal investment  $L_t$  and decisions on whether to payout ( $dD_t > 0$ ) or buy back tokens ( $D_t < 0$ ) all depend on  $m_t$  only.

(iii) Users' optimal token holdings and participation decisions, together with the user base depend on both  $m_t$  and  $A_t$ , according to Proposition 2.

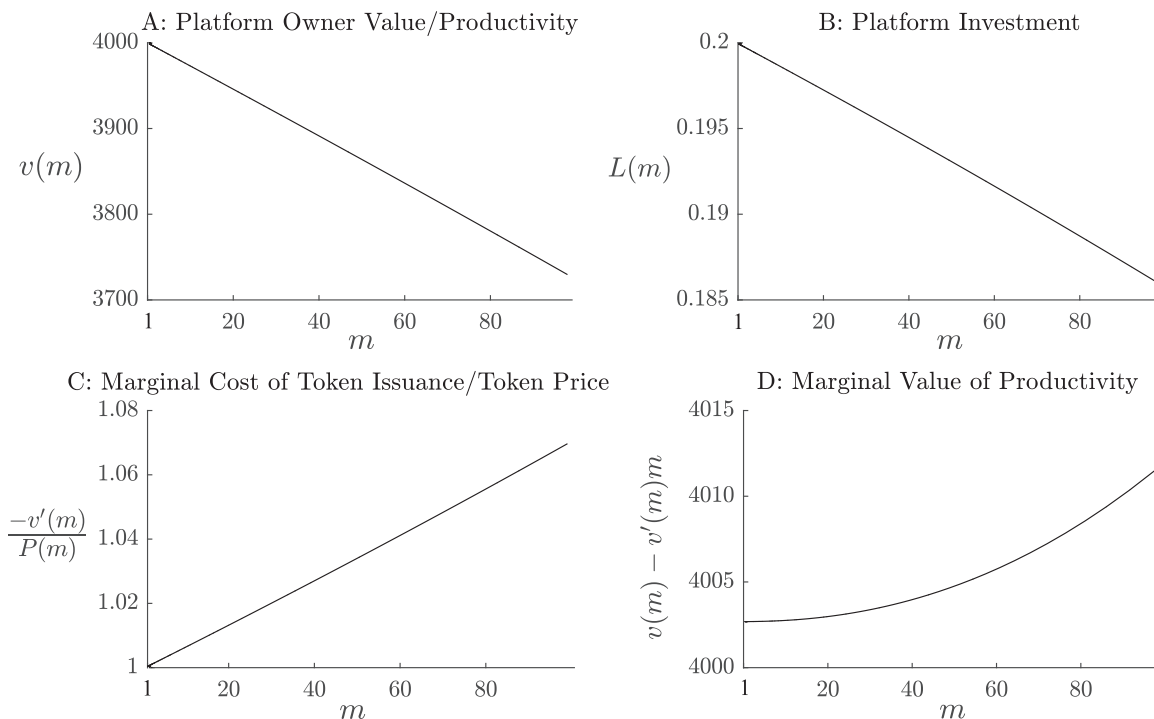
For the parameters that affect user activities, we follow CLW to set  $\alpha = 0.3$ ,  $\phi = 1$ ,  $r = 0.05$ , and the volatility parameter,  $\sigma^H = 2$ . For the mean productivity growth, we set  $\mu^H = 0.5$ , which generates a  $\mu_t^P$  in line with the values in CLW. We set  $\chi = 7\%$  for the financing cost following empirical studies on equity issuance (Eckbo et al., 2007). We set  $\theta = 10,000$  so the growth rate of productivity is in line with that in CLW. The rest of parameters are to illustrate the qualitative implications of the model:  $\gamma = 1/8$  for the network effect and  $\xi = 2$ ,  $\kappa = 5/8$ , and  $\omega = 100$  for the distribution parameters of  $u_i$ . The model's qualitative implications are robust to the choice of these parameters.

Blockchain platforms often feature a maximum total token supply. One way to incorporate this into our framework is to have an absorbing upper bound of  $m_t$ , say  $\tilde{m}$ . In such case, once reaching a multiple of the platform productivity, i.e.,  $\tilde{m}A_t'$ , the supply would grow proportionally with  $A_t'$  forever, and according to Lemma 2, token price will then be a constant. As for newly issued tokens, they are divided between the entrepreneur and contributors, and here the entrepreneur faces a standard consumption-savings trade-off: If she takes a larger share of the new tokens, the productivity grows slower. We leave this extension for future research.

#### 4.2. Endogenous platform development

In Panel A of Fig. 2, we plot the  $A'$ -scaled value function  $v(m_t)$ . The curve starts at the payout boundary where the entrepreneur receives payouts in the form of newly issued tokens, and it ends at the buyback boundary where the entrepreneur raises funds to buy back and burn tokens out of circulation in order to support token price and the continuation value.

The entrepreneur's value declines in the normalized token supply (a notion of “inflation” practitioners casually refer to). Intuitively, when more tokens are circulating relative to productivity, it is more likely for the entrepreneur to reach the buyback (upper) boundary and pay the financing cost, and in the less likely event of token payout, the entrepreneur receives a lower value due to the depressed token price. The value function is always positive in Panel A, suggesting that the entrepreneur never abandons the platform.



**Fig. 2.** Platform value and investment. In Panel A, we plot the  $A'_t$ -scaled value function. Panel B plots the optimal investment as a function of productivity-normalized token supply,  $m_t$ . Panel C shows the ratio of the entrepreneur's marginal value of tokens to the market price of tokens, and the wedge between this ratio and one represents the token issuance cost. Panel D shows the entrepreneur's marginal value of  $A'_t$ .

In Panel B of Fig. 2, we plot the optimal platform investment (given by Eq. (27)) against the normalized token supply. In Eq. (27), the optimal  $L_t^*$  decreases in  $-V_{M_t}/P_t$ , the ratio of the marginal cost of token issuance,  $-V_{M_t} = -v'(m_t)$ , to the token market price,  $P_t$ . This ratio measures the valuation gap between the entrepreneur and the platform users (i.e., the token issuance cost). When the gap is high, it is costly from the entrepreneur's perspective to finance investment with tokens. The ratio starts at one, as implied by the value-matching condition of the payout boundary. This is when the entrepreneur's private valuation of tokens, which incorporates the expected cost of token buyback, coincides with the market or users' valuation. The gap widens as the token supply outpaces the growth of the effective productivity, i.e., as  $m_t$  increases, and eventually, when the gap reaches  $(1 + \chi)$ , the entrepreneur optimally buys back tokens. The increasing token issuance cost in Panel C (i.e.,  $-V_{M_t}/P_t$  increasing in  $m_t$ ) largely contributes to the decreasing pattern of  $L_t^*$ .

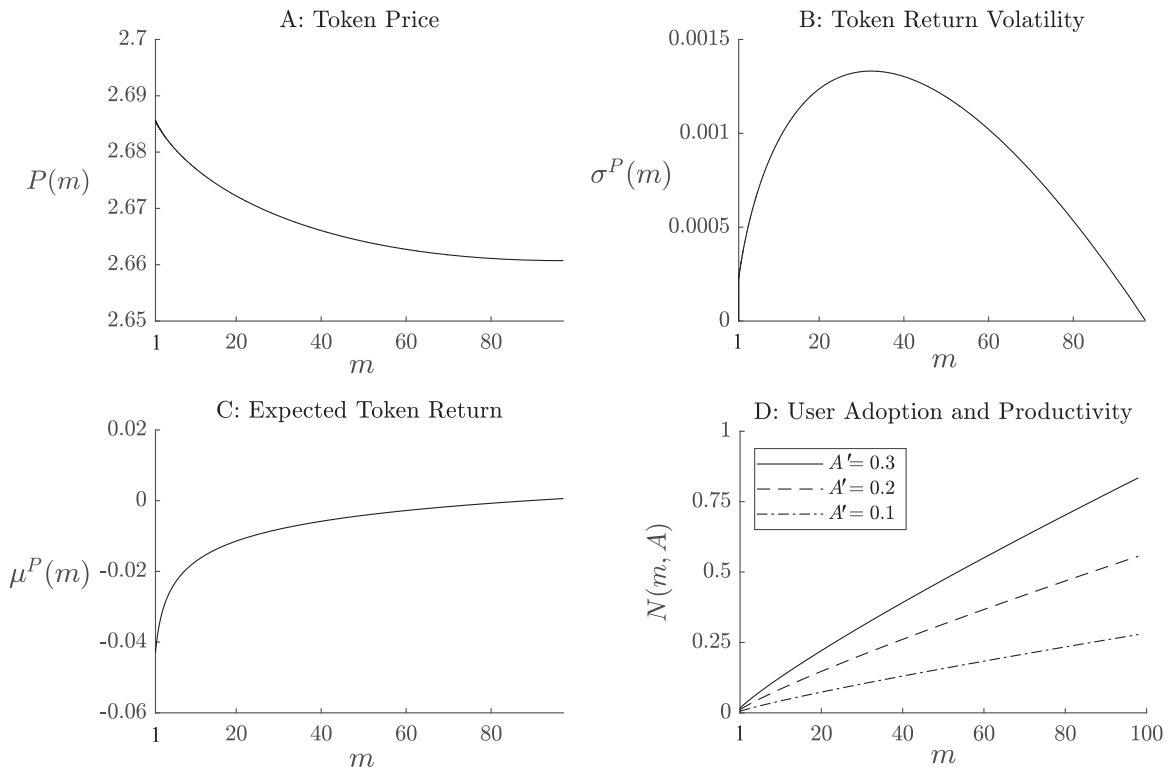
The optimal  $L_t^*$  given by Eq. (27) increases in the marginal value of effective productivity,  $\frac{\partial V_t}{\partial A'_t} = v(m_t) - v'(m_t)m_t$ , because on average, investment has a positive outcome, i.e.,  $\mu^H > 0$ , so more resources gathered by token payments,  $L_t$ , leads to a higher expected growth of  $A_t$  and an expected increase in the entrepreneur's value. Moreover, the marginal value of effective productivity also has a positive impact on  $L_t^*$  via the denominator of  $L_t^*$  in Eq. (27). As shown in the HJB Eq. (26), the marginal value of  $A'_t$  is multiplied by the drift of  $A'$  ( $= A_t^\delta$ ), which is equal to  $\delta\mu^H L_t + \frac{1}{2}\delta(\delta - 1)(\sigma^H)^2 L_t^2$  given  $dA_t$  in Eq. (2).

denominator effect follows the quadratic term in the drift of  $A'_t$ . Near the buyback (upper) boundary,  $\frac{\partial V_t}{\partial A'_t}$  is particularly high because an increase in  $A'_t$  pulls down  $m_t$  and thus reduces the likelihood of costly buyback. Overall, even though the marginal value of productivity is increasing in  $m_t$  in Panel D, the economic force of token overhang (Panel C) dominates, resulting in an optimal investment that declines in the normalized token supply  $m_t$ .

Finally, according to Eq. (27), the second-order derivative of the  $A'$ -scaled value function,  $v''(m_t)$ , also affects the optimal investment  $L_t^*$  via the denominator. Its impact is small under the current parameterization, so the plot is not included in Fig. 2. However, the intuition of the potential precautionary motive ( $v''(m_t) < 0$ ) is still interesting. Token payout is largely a real option decision. While it is not completely irreversible, reversing it (i.e., buying back tokens) incurs the financing cost.<sup>27</sup> The probability of incurring such cost increases as  $m_t$  approaches the buyback boundary, so the entrepreneur becomes increasingly cautious on making a risky investment given the shock in Eq. (2). Therefore, the negative impact of precaution on investment is more prominent near the buyback (upper) boundary of  $m_t$ .

Overall, our model reveals a rich set of trade-offs in the choice of token-financed investment. The model has the potential to explain various features of token distribution

<sup>27</sup> For example, the Synereo team has to hold multiple meetings and incur effort cost to explain to users when the team burned 33% of its cryptocurrency reserves.



**Fig. 3.** Token price Dynamics and user adoption. In Panel A, we plot token price against productivity-normalized token supply,  $m_t$ . In Panel B, we plot  $\sigma_t^P$ , the  $P_t$ -scaled diffusion term of token price. In Panel C, we show the  $P_t$ -scaled drift of token price. In Panel D, we plot the user base, which depends on both  $m_t$  and  $A'_t$ .

to open-source engineers, miners (ledger maintainers), and crowd-sourced financiers in practice.

### 4.3. Token price and user adoption

The dynamics of token price are directly linked to that of productivity-normalized token supply. As shown in Panel A of Fig. 3,  $P_t$  declines in  $m_t$ . In Appendix C, we derive the negative shock loading (diffusion) of  $m_t$ . Thus, a positive shock in productivity decreases  $m_t$  by increasing  $A'_t$ , thus moving the economy closer to the payout (lower) boundary of  $m_t$ . Token price increases in response and is therefore procyclical with respect to productivity shock. In stark contrast to the 200% per annum volatility of productivity shock that we input, i.e., the fundamental volatility,  $\sigma_t^P$  is surprisingly small (below 0.15% in Panel B of Fig. 3) because the entrepreneur receives newly issued tokens as payout when  $m_t$  is low and raise funds to buy back and burn tokens when  $m_t$  is high, actively moderating the variation of the token price by controlling the supply. The entrepreneur’s incentive to regulate the token supply is governed by her marginal cost of raising token supply,  $-\frac{\partial v_t}{\partial m_t} = v'(m_t) < 0$ . Corollary 2 directly follows from Corollary 1.

**Corollary 2.** From Corollary 1, the token price is bounded in  $\left[-\left(\frac{1}{1+\chi}\right)v'(m_t), -v'(m_t)\right]$ .

The optimality condition on payout imposes an upper bound on token price. At any  $m_t$ ,  $P(m_t) \leq -v'(m_t)$  because

otherwise the entrepreneur prefers obtaining token payout (worth  $P(m_t)$  per unit of token) over preserving the continuation value (worth  $-v'(m_t)$ ). The optimality condition on token buyback imposes a lower bound on token price.

At any  $m_t$ ,  $P(m_t) \geq -\left(\frac{1}{1+\chi}\right)v'(m_t)$  because otherwise the entrepreneur finds tokens too cheap in the secondary market and prefers raising costly funds to buy back tokens. In our model, the token value has two anchors. First, users need tokens for transactions. Second, to preserve the continuation value, the entrepreneur is willing to pay the financing cost to raise funds and use such real resources to buy back and burn tokens out of circulation.

Panel C of Fig. 3 shows the expected token price change. When  $m_t$  is low, the expectation is negative, reflecting the likely token-supply increase due to token payout to the entrepreneur and increasing investment needs (Panel A of Fig. 2). As  $m_t$  increases, the expected change in token price gradually increases and eventually becomes positive because, first, the investment needs decline, and second, the likelihood of token buyback increases.

Finally, we report the results on user-base dynamics. As shown in Proposition 2, unlike other endogenous variables that only depends on  $m_t$ , the user base  $N_t$  depends on both  $m_t$  (through the expected token price change  $\mu^P(m_t)$ ) and  $A'_t$ . In Panel D of Fig. 3, we plot the user base against  $m_t$  under different values of  $A'_t$ . Given  $A'_t$ , Panel D shows that as  $m_t$  increases (and  $\mu_t^P$  increases), the user base increases because agents expect an improving capital gain



from token holdings. Given any value  $m_t$ , a higher value of productivity  $A_t$  leads to a larger user base because  $A_t$  directly enters users' convenience yield from token holdings in Eq. (3).

Our model features mild volatility in the token price. The entrepreneur's optimal payout and token buyback decisions impose two reflecting boundaries on the state variable  $m_t$ . At both boundaries, the first derivative of token price with respect to  $m_t$  must be zero (e.g., see Eq. (30)) because otherwise arbitrage opportunities emerge: For example, at  $\underline{m}$ ,  $m_t$  will be reflected upward, so  $P'(m_t) > 0$  ( $< 0$ ) implies guaranteed instantaneous profits from a long (short) position. By Itô's lemma,  $P'(m_t) = 0$  at the boundaries implies  $\sigma^P(m_t) = 0$ . Therefore, even in the interior region, token volatility  $\sigma^P(m_t)$  can exceed zero; however, it cannot go far beyond zero as it is tied to zero at both boundaries.

Therefore, in our model, the stability of token price relies on the dynamic payout and token buyback decisions of the entrepreneur. This mechanism differs significantly from the stablecoin designs proposed by practitioners. A popular approach is to mimic open market operations by central banks. When token price is low, the platform issues token bonds to buy back tokens. Token bonds promise to pay the principal with interest in the future, but all payments are in tokens. The problem with this design is that an inter-temporal substitution between current and future tokens does not introduce any real resources to support the token price, nor does it provide any incentive to economic agents to devote such resources. A champion of this design, the Basis stablecoin project, which attracted \$133 million of venture capital in April 2017, has closed down all operations, citing US securities regulations as the reason for its decision. An alternative design is collateralization, which backs token value with real resources, such as the US dollar (e.g., Tether, Circle, Gemini, JPM coin, or Paxos), oil reserves (e.g., Venezuela's El Petro, OilCoin, or PetroDollars)<sup>28</sup> A derivative of such design is to further tranche the claims on real resources, so tokens are the most senior tranche, which is less information-sensitive and thus has a stable secondary-market value. Li and Mayer (2020) provide a model on collateralized stablecoins.

#### 4.4. Comparative statics

We further explore the mechanism of underinvestment by analyzing the comparative statics. Specifically, we focus on the root of the problem, which is the cost of external financing for token buyback, and by comparing platforms with different degrees of network effects, we highlight the key role of risk in generating underinvestment. In Appendix D, we explore how competition (captured by the parameters  $\omega$  and  $\kappa$ ) and user distribution (captured by the parameter  $\xi$ ) affect the platform value and optimal investment strategy.

##### 4.4.1. External financing cost

The entrepreneur's external financing cost drives the divergence of interest between the entrepreneur and users. If the cost of buyback,  $\chi$ , is zero, the dynamic token issuance cost and thus underinvestment disappear as shown in Eq. (10) because  $-V_{M_t} = P_t$ .<sup>29</sup> We now compare the model's performances under  $\chi = 7\%$  (the baseline value) and  $\chi = 8\%$ .

In Panel A of Fig. 4, we see that the entrepreneur's ( $A'$ -scaled) value function curve ends at a lower level of  $m_t$  when  $\chi$  is higher. While the buyback (right) boundary is lower, the payout (left) boundary remain roughly unchanged. Therefore, the overall level of  $m_t$  is lower when  $\chi$  increases. When the financing cost is higher, the entrepreneur faces a higher cost of issuing tokens. Therefore, the entrepreneur optimally maintains a low level of normalized token supply. Panel A of Fig. 4 also shows that, intuitively, a higher external financing cost causes the value function to shift downward across different values of  $m_t$ .

We compare platform investment under different values of  $\chi$  in Panel B of Fig. 4. A higher financing cost leads to lower investment as the conflict of interest between the entrepreneur and users is exacerbated. Following a positive shock, the investment successfully enhances productivity, benefiting both the entrepreneur and users; following a negative shock, only the entrepreneur bears the downside of a higher likelihood of paying the financing cost for token buyback because users are free to reduce token holdings and abandon the platform. A higher financing cost implies a greater downside for the entrepreneur.

##### 4.4.2. Network effect

As specified in Eq. (3), the parameter  $\gamma$  governs the strength of the network effect. When  $\gamma$  is higher, an increase in the total number of users,  $N_t$ , causes each user to demand more tokens. In Fig. 5, we compare the entrepreneur's value function (Panel A) and optimal investment (Panel B) under  $\gamma = 0.125$  (the baseline value) and  $\gamma = 0.124$ .

Interestingly, a weaker network effect induces the entrepreneur to be more aggressive in token issuance. Moreover, the entrepreneur's value function shifts upward (Panel A), as a weaker network effect induces more investment (Panel B). These observations are counterintuitive because when the network effect is weaker, the positive feedback effect of increasing productivity to attract more and more users is dampened, which discourages investment in productivity. However, our model features a counteracting force.

As previously discussed, the conflict of interest between the entrepreneur and users and the resultant underinvestment problem depend on three ingredients: (1) the external financing cost, (2) user heterogeneity, and (3) the uncertainty in investment outcome. When investment outcome is uncertain, the entrepreneur has to consider the potential downside, i.e., the increase in the likelihood

<sup>28</sup> Such designs are often subject to manipulations (e.g., Griffin and Shams, 2020).

<sup>29</sup> In this case, the HJB equation of the owner's valuation function degenerates. Once the token price is solved via the ODE implied by the token market-clearing condition, the owner's value function can be calculated as an integral of token price, because  $-V_{M_t} = -V'(m_t) = P(m_t)$ .

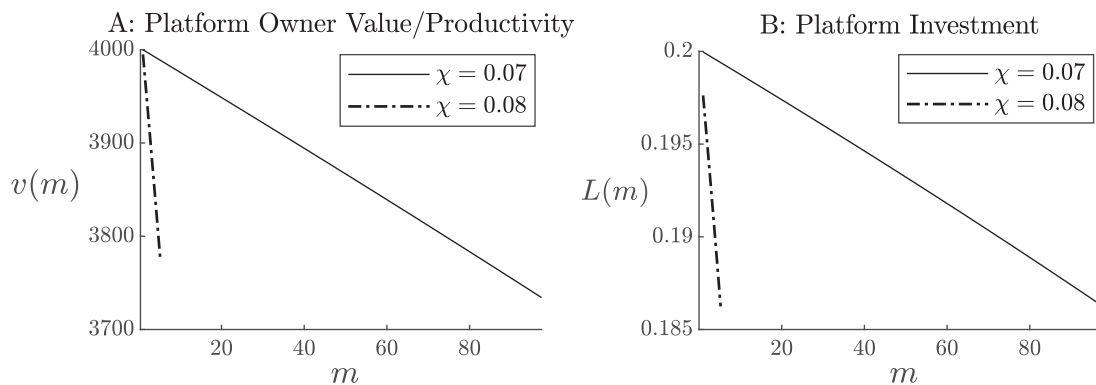


Fig. 4. Comparative statics: financing cost. This figure shows the  $A'$ -scaled value function (Panel A) and optimal investment (Panel B) under  $\chi = 0.08$  and the baseline value  $\chi = 0.07$ .

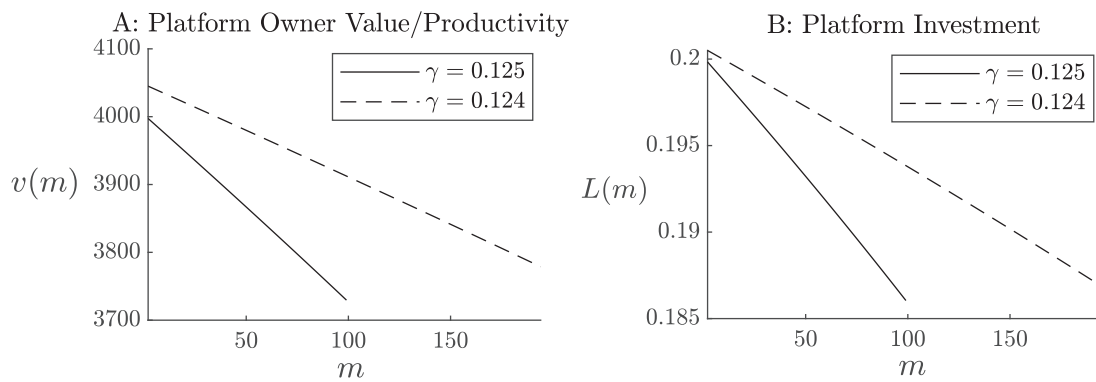


Fig. 5. Comparative statics: network effect. This figure shows the  $A'$ -scaled value function (Panel A) and optimal investment (Panel B) under  $\gamma = 0.124$  and the baseline value  $\gamma = 0.125$ .

of costly token buyback follows a negative shock that increases  $m_t$  (by decreasing productivity in the denominator). A weaker network effect dampens uncertainty. Following a positive shock, investment increases productivity, but under a weaker network effect, the resultant increase in token demand and the price is smaller. Likewise, following a negative shock, a weaker network effect implies a smaller decline in token demand and price. Therefore, even though a weaker network effect reduces the average positive impact of investment on token price and the entrepreneur's payout (the mean effect), it also dampens the risk of investment, which is a key ingredient of the underinvestment problem.

### 5. Blockchain and investment efficiency

The entrepreneur faces a time inconsistency problem that features prominently in studies on macroeconomics (e.g., Kydland and Prescott, 1980; Barro and Gordon, 1983; Lucas and Stokey, 1983) and corporate capital structure (e.g., DeMarzo and He, 2021). If the entrepreneur is able to commit against underinvestment, the users would have demanded more tokens, which then increases the token price, as well as the value of token payouts to the entrepreneur. However, a predetermined level of investment can be deemed suboptimal ex post as the conflict of inter-

est arises between the entrepreneur and users, reflected in the gap between the entrepreneur's private valuation of tokens,  $-V_{M_t}$ , and users' valuation,  $P_t$ .

So far, we have focused on the discretionary token-supply policies of the platform. Next, we study how commitment to predetermined token-supply rules adds value. Our analysis provides insights on why tokens become a viable payment solution after the blockchain technology matures. The rise of tokens as a means of payment on digital platforms is a recent phenomenon with many applications inspired by the success of Bitcoin, Ethereum, and other blockchain-based startups. In Appendix A, we summarize the three aspects of blockchain technology that are critical in enabling commitment, including data structure, smart contracting, and decentralized governance, and we highlight both the advantages of blockchain-based commitment over traditional approaches (e.g., collateral) and its limitations.

#### 5.1. Constant token growth as commitment to investment

To illustrate the impact of commitment brought forth by the blockchain technology, we consider a specific case where:

$$dM_t = F(L_t, A_t)/P_t dt = \mu^M M_t dt, \tag{34}$$

i.e., a constant growth rate of token supply in the interior region ( $dD_t = 0$ ) is used to finance the enhancement of platform productivity. This commitment is popular among blockchain applications primarily as a way to address users' concerns over token-holding dilution via inflation.<sup>30</sup> We show that the fundamental role of such commitment actually lies in the mitigation of underinvestment. This rule of token supply implies that the resources a platform gathers,  $L_t$ , become a predetermined function of the state variables.

We still allow the entrepreneur to receive token dividends and buy back tokens, but with  $L_t$  following a predetermined rule, the entrepreneur's only control variable is  $dD_t$ . The following HJB equation characterizes the value function:

$$rV(M_t, A_t)dt = \max_{dD_t} P_t dD_t [\mathbb{I}_{\{dD_t \geq 0\}} + (1 + \chi) \mathbb{I}_{\{dD_t < 0\}}] + V_{M_t} (\mu^M M_t dt + dD_t) + V_{A_t} A_t L_t \mu^H dt + \frac{1}{2} V_{A_t A_t} A_t^2 L_t^2 (\sigma^H)^2 dt. \quad (35)$$

Comparing it with Eq. (9), the tokens used to pay for  $L_t$  is replaced by  $\mu^M M_t dt$ . Under the same change of variable as in Section 4.1, we have, in the interior region ( $dD_t = 0$ )

$$rv(m_t) = v'(m_t) \frac{(L_t + \frac{\theta}{2} L_t^2)}{P(m_t)} + [v(m_t) - v'(m_t) m_t] \times \left[ \delta \mu^H L_t + \frac{1}{2} \delta (\delta - 1) (\sigma^H)^2 L_t^2 \right] + \frac{1}{2} v''(m_t) m_t^2 \delta^2 (\sigma^H)^2 L_t^2, \quad (36)$$

where  $L_t$ , as a function of  $m_t$ , is implicitly defined by:

$$L_t + \frac{\theta}{2} L_t^2 = \mu^M P(m_t) m_t. \quad (37)$$

As the left-hand side of Eq. (37) is an increasing and convex function of  $L_t$ , investment increases in the  $A'$ -scaled token market capitalization, i.e.,  $P(m) m = P_t M_t / A'_t$ . Intuitively, when tokens are more valuable, the constant growth of token supply gathers more resources for development. The boundary conditions are the same as those of the baseline model.

*Proposition 5* (Solution under Predetermined Token Growth). *Under the commitment to a constant growth rate of token supply for investment in productivity, the investment given by Eq. (37) increases in  $A'$ -scaled token market capitalization, i.e.,  $P_t m_t$ . The entrepreneur receives token dividends ( $dD_t^* > 0$ ) when  $P_t \geq -V_{M_t}$ , and buys back and burns tokens out of circulation ( $dD_t^* < 0$ ) when  $-V_{M_t} \geq P_t (1 + \chi)$ . Token price is determined by Eq. (23) as in the baseline model.*

In our numerical solution, we start with  $\mu^M = 2$  for illustrative purpose. Comparing Panel A of Fig. 6 with Panel A of Fig. 2, we can see that the commitment increases the entrepreneur's value by around 15% near the

payout (lower) boundary and around 20% near the buy-back (upper) boundary. By comparing Panel B in the two figures, we see that such an increase mainly comes from a higher level of investment as the commitment mitigates the problem of underinvestment under token overhang.

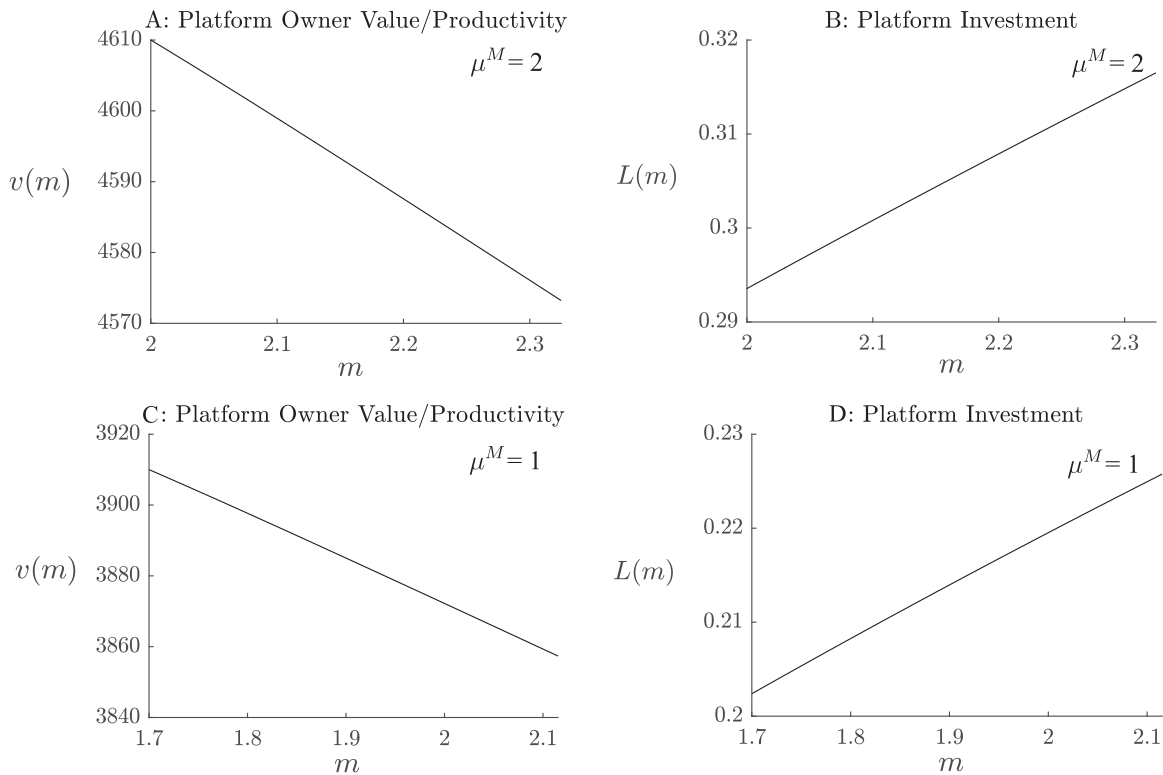
As previously discussed, to the entrepreneur, the value of tokens is  $-V_{M_t}$ , while to the users, it is  $P_t$ . The wedge between  $-V_{M_t}$  and  $P_t$  widens as the normalized token supply,  $m_t$ , increases, and the ratio,  $-V_{M_t}/P_t$ , reaches  $1 + \chi$ , the financing cost of token buyback, at the buyback (upper) boundary of  $m_t$ . Therefore, as shown in Eq. (10), the closer to the buyback boundary, the more concerned the entrepreneur is over the token issuance cost,  $-V_{M_t}/P_t > 1$ . This implies that investment chosen by the entrepreneur declines in  $m_t$ , as shown in Panel B of Fig. 2. Therefore, commitment to the predetermined investment rule creates more value when  $m_t$  is higher and closer to its upper boundary. This explains why the commitment-induced improvement in the entrepreneur's value is greater near the buyback boundary (around 20% increase) than near the payout boundary (around 15% increase).

Another difference between the commitment case and the baseline case of discretionary investment is that under commitment, investment increases in  $m_t$  (Panel B of Fig. 6), while in the baseline case, investment decreases in  $m_t$  (Panel B of Fig. 2). As previously discussed, the declining pattern in the baseline case is due to the increasing cost of issuing tokens, i.e., the widening wedge between  $-V_{M_t}$  and  $P_t$ . The increasing pattern in the commitment case is a numeric result. As  $m_t$  increases, token price,  $P(m_t)$ , decreases, but the  $A'_t$ -scaled market capitalization, i.e.,  $P(m_t) m_t$ , may increase or decrease. Under the current parameterization, the  $P(m_t) m_t$  increases in  $m_t$ , so, according to Eq. (37),  $L_t$  increases in  $m_t$ .

To further demonstrate the economic mechanism, we also consider the solution when the committed growth of token supply is half as large, i.e.,  $\mu^M = 1$ . The impact of reducing token-supply growth rate on investment and the entrepreneur's value is unclear a priori. By reducing inflation, a lower growth rate of token supply tends to increase the token price that users are willing to pay and thus increase  $L_t$ , the resources gathered via token issuance. However, as shown in Eq. (37),  $L_t$  depends on the token market capitalization, i.e., both the unit price and the quantity of tokens, so reducing the token-supply growth can also negatively impact  $L_t$ . Under the current parameterization, the latter force dominates, which leads to a lower level of investment under  $\mu^M = 1$  (Panel D of Fig. 6) than the solution under  $\mu^M = 2$  (Panel B of Fig. 6). Comparing Panels A and C of Fig. 6, we can see that the entrepreneur's value also declines when  $\mu^M$  declines from 2 to 1.

What is more interesting is that the entrepreneur's value near the payout (lower) boundary of  $m_t$  is not only below the value under  $\mu^M = 2$  but also around 2% below the value in the baseline case of discretionary investment (Panel A of Fig. 2). As previously discussed, the wedge between the entrepreneur's private cost of token issuance,  $-V_{M_t}$ , and users' valuation,  $P_t$ , widens as  $m_t$  increases, so commitment adds more value when  $m_t$  is higher. Indeed, the entrepreneur's value is around 3% higher under  $\mu^M = 1$  than in the discretionary case near the buyback (upper)

<sup>30</sup> Blockchain applications emphasize predetermined rules of token-supply growth. Ethereum has roughly fixed increments while Bitcoin's minting rate is a constant that halves as the system matures via a longer transaction chain (specifically, every 210,000 more blocks).



**Fig. 6.** Platform value and investment under predetermined token-supply growth. In Panels A and C, we plot the  $A_t^i$ -scaled value functions under  $\mu^M = 2$  and  $\mu^M = 1$ , respectively. In Panel B and D, we plot the optimal investment under  $\mu^M = 2$  and  $\mu^M = 1$ , respectively.

boundary. In contrast, commitment adds less value in the low- $m_t$  region, i.e., near the payout (lower) boundary, because the conflict of interest between the entrepreneur and users is less severe. Therefore, near  $m$ , the value added from commitment is small while the drawback of commitment—the entrepreneur cannot coordinate investment ( $L_t$ ) and payout/buyback ( $dD_t$ ) decisions—dominates. As a result, the entrepreneur's value actually decreases under commitment relative to the discretionary case.

Regarding the coordination between investment and payout/buyback decisions, its importance can be seen from the difference in the range of  $m_t$  on the horizontal axis between commitment cases (Fig. 6) and the baseline case (Figs. 2 and 3). Under commitment, the range is much smaller. The entrepreneur pays the financing cost to buy back and burn tokens at a much lower level of  $m_t$  (i.e., chooses a lower buyback boundary). Moreover, the payout boundaries under commitment (both  $\mu^M = 1$  and  $\mu^M = 2$ ) are higher than that of the discretionary case. Therefore, when the entrepreneur loses control of the amount of tokens issued for investment, she turns more active in payout and buyback, effectively narrowing the equilibrium range of  $m_t$ . This results in more frequent payments of the financing cost.

To sum up, commitment to predetermined investment rules adds value by addressing the token overhang problem, but it also forces the entrepreneur to control the token supply more actively via the remaining margins (i.e.,

payout and buyback), and to pay the financing cost more frequently. Overall, when the former force dominates, the entrepreneur obtains a higher value via commitment: A higher level of investment translates into a higher token price through users' expectations of faster productivity growth, and a higher token price in turn implies a more valuable token payout for the entrepreneur.

### 5.2. Mitigating underinvestment through fees

As demonstrated, commitment enabled by blockchains mitigates the problem of token-overhang and underinvestment, but commitment to predetermined investment rules forces the entrepreneur to manage the token supply through more active payout and buyback, which results in paying financing costs more frequently. An alternative solution is to finance investment with fees collected from users.

To analyze the impact of fees, let  $f_{0,t}$  and  $f_{1,t}$  denote respectively the fixed and proportional fees users pay at  $t$ . The users' objective Eq. (6) is modified to:

$$\max \left\{ 0, \max_{k_{i,t} > 0} \left[ (P_t k_{i,t})^{1-\alpha} (N_t^\gamma A_t u_i)^\alpha dt + k_{i,t} \mathbb{E}_t [dP_t] - (\phi + f_{t,0})dt - P_t k_{i,t} (r + f_{1,t})dt \right] \right\}. \quad (38)$$

Under the parameterized distribution of  $u_i$ , we follow the same procedure to solve the participation threshold and

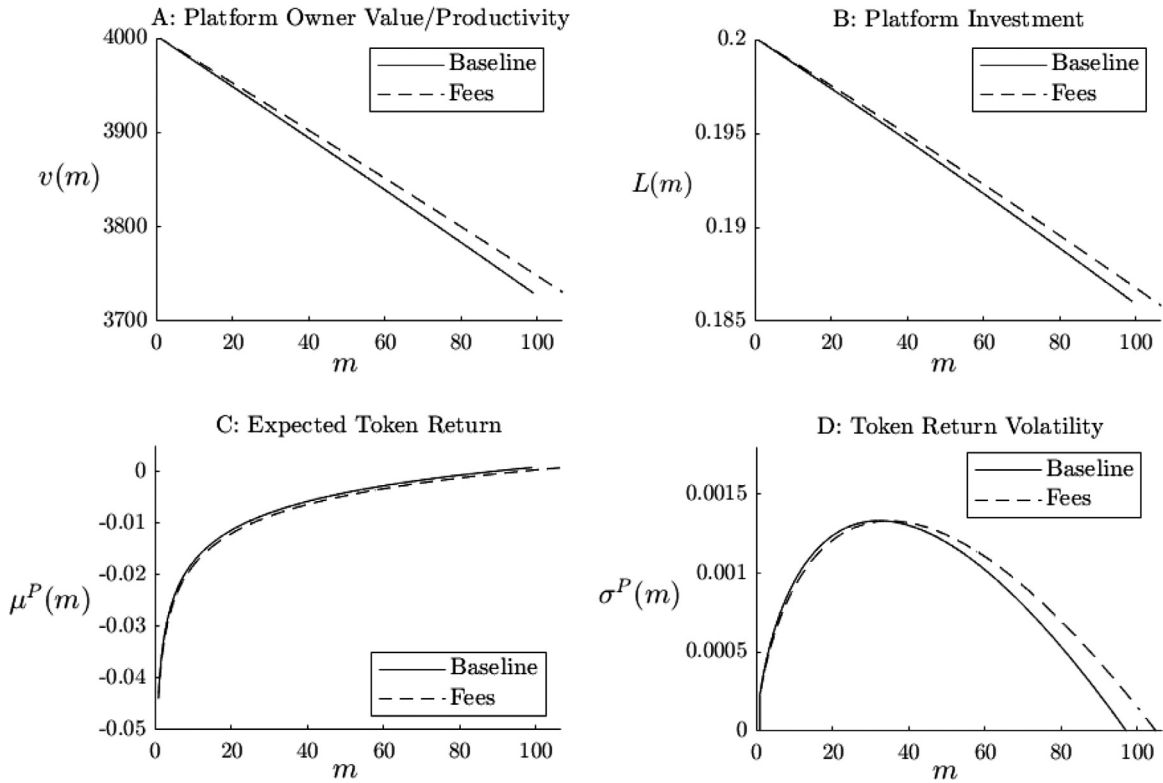


Fig. 7. Platform value, investment, and token price dynamics under fees. In Panel A, B, C, and D, we compare, respectively, the entrepreneur’s  $A_t^i$ -scaled value function, optimal investment, the  $P_t$ -scaled token-price drift, and the  $P_t$ -scaled token-price diffusion under fees and in the baseline case without fees.

then obtain a new measure of users:

$$N_t = A_t^i \left( \frac{\alpha}{\omega(\phi + f_{0,t})} \right)^{\frac{\xi}{1-\xi\gamma}} \left( \frac{1-\alpha}{r + f_{1,t} - \mu^P(m_t)} \right)^{\left(\frac{\xi}{1-\xi\gamma}\right)\left(\frac{1-\alpha}{\alpha}\right)} \equiv A_t^i n(f_{0,t}, f_{1,t}, m_t). \tag{39}$$

It is clear that  $\frac{\partial n(f_{0,t}, f_{1,t}, m_t)}{\partial f_{0,t}} < 0$  and  $\frac{\partial n(f_{0,t}, f_{1,t}, m_t)}{\partial f_{1,t}} < 0$  (as  $\alpha \in (0, 1)$  and  $\xi \in (1, 1/\gamma]$ ). The platform faces a trade-off. Higher fees, either via  $f_{0,t}$  or  $f_{1,t}$ , lead to lower user participation, which directly reduces the revenue from fixed fees, i.e.,  $f_{0,t}N_t$ .<sup>31</sup>

Meanwhile, higher fees also reduce users’ token demand, which leads to a lower token price and proportional fees. We follow the same procedure of solving users’ token demand,  $k_{i,t}$ , and then from the token market-clearing condition, we obtain:

$$P(f_{0,t}, f_{1,t}, m_t) = \frac{\xi}{m_t(\xi - 1)\omega^{\frac{\xi}{1-\xi\gamma}}} \left( \frac{\alpha}{\phi + f_{0,t}} \right)^{\frac{\xi}{1-\xi\gamma} - 1} \times \left( \frac{1-\alpha}{r + f_{1,t} - \mu^P(m_t)} \right)^{1 + \left(\frac{\xi}{1-\xi\gamma}\right)\left(\frac{1-\alpha}{\alpha}\right)}. \tag{40}$$

<sup>31</sup> Note that the users’ expectations of the rate of token price change,  $\mu^P(m_t)$ , is a function of the key state variable  $m_t$ , which the platform takes as given when choosing its fees.

We have  $\frac{\partial P(f_{0,t}, f_{1,t}, m_t)}{\partial f_{0,t}} < 0$  and  $\frac{\partial P(f_{0,t}, f_{1,t}, m_t)}{\partial f_{1,t}} < 0$  (as  $\frac{\xi}{1-\xi\gamma} - 1 > 0$  under  $\xi\gamma < 1$ ), so the token price is negatively affected by the platform imposing fees on users.

Overall, when choosing fees, the entrepreneur solves a problem akin to a monopolistic producer, trading off unit prices and quantities. The total fee revenues are equal to  $f_{0,t}N_t + f_{1,t}P_tM_t$ , where we apply the token market-clearing condition,  $\int_{i \in [0,1]} k_{i,t} di = M_t$ , to substitute out  $k_{i,t}$ . Such revenues can be used to finance investment in productivity so that the need to issue tokens is reduced. The new law of motion of token supply is thus given by:

$$dM_t = \frac{F(L_t, A_t) - (f_{0,t}N_t + f_{1,t}P_tM_t)}{P_t} dt + dD_t, \tag{41}$$

and in the interior region where  $dD_t = 0$ , the platform’s HJB Eq. (9) becomes:

$$rV(M_t, A_t)dt = \max_{\{f_{0,t}, f_{1,t}, L_t, dD_t\}} \times V_{M_t} \left[ \frac{F(L_t, A_t) - (f_{0,t}N_t + f_{1,t}P_tM_t)}{P_t} dt \right] + V_{A_t} A_t L_t \mu^H dt + \frac{1}{2} V_{A_t A_t} A_t^2 L_t^2 (\sigma^H)^2 dt. \tag{42}$$

Under a negative marginal value of outstanding token supply, i.e.,  $V_{M_t} < 0$ , the entrepreneur chooses fees to minimize the expression in the square bracket on the right-hand side of Eq. (42). Allowing the platform to charge fees provides an additional source of revenue that



likely increases investment and the entrepreneur's value, especially when the likelihood of costly token buyback is high near the upper (buyback) boundary of  $m_t$ .

Introducing fees entails costs and benefits that are associated with traditional platform businesses. There are many studies on the complex economic forces that drive the determination of fees on platforms (e.g., Hagi, 2006; Rochet and Tirole, 2006; Rysman, 2009). Given our focus on tokens, our setup does not capture all those forces. Therefore, we do not address the question of optimal fee setting. Instead, we illustrate the impact of fees in Fig. 7 using a particular fee structure,  $f_{0,t} = 0.1\%$  and  $f_{1,t} = 0.1\%$ .<sup>32</sup> The fee revenue,  $f_{0,t}N_t + f_{1,t}P_tM_t$ , varies endogenously in the model, along with the user base,  $N_t$ , the token price,  $P_t$ , and the outstanding token amount,  $M_t$ . The constant fee parameters allow us to remain as close as possible to the baseline model and its solution method.

The dashed line in Panel A of Fig. 7 shows that fees increase the platform owner's value especially near the buyback (upper) boundary of  $m_t$ . As previously discussed, near the upper boundary, the token issuance cost is high, so the platform refrains from token-financed investment. This underinvestment problem is now mitigated by fee revenues (Panel B of Fig. 7). Introducing fees does not significantly affect the dynamics of the token price (Panels C and D of Fig. 7) in terms of the drift and diffusion. A notable difference between our main model and the model with fees is that under fees, the entrepreneur delays costly token buyback, which is reflected in a higher upper boundary of  $m_t$  (Panel D of Fig. 7). This additional financial slack also helps to boost the entrepreneur's value.

Overall, fees increase the entrepreneur's value by both alleviating the underinvestment problem and allowing the platform to reduce the impact of financing costs by postponing token buybacks. Our analysis thus points towards an interesting direction for future research: Analogous to macroeconomic management through monetary and fiscal policies, a platform may dynamically manage its state-contingent token-supply policy and fee structure.

## 6. Conclusion

We develop a dynamic model of a platform economy, where tokens are used as a means of payment among users and issued to finance platform operation and growth. Tokens facilitate user transactions and compensate distributed ledger-keepers, open-source developers, and crowdfunders for their contributions to platform development. The platform owners maximize their seigniorage by managing token supply, subject to the conditions that users optimally decide on token demand and rationally form expectations of token price dynamics.

We characterize the optimal token-supply strategy and its implications for user-base dynamics, endogenous plat-

form growth, and token price dynamics. A key mechanism is the wedge between insiders' (the platform owners') token valuation and that of outsiders (users). When the valuation wedge falls to zero, the platform owners optimally receive token dividends; when it rises to an endogenously determined threshold, the platform optimally burns tokens out of circulation to stabilize the token value. The wedge creates underinvestment in platform productivity under the financing cost of token buyback.

By enabling commitment, blockchains enable rule-based token supply, thereby mitigating underinvestment by overcoming the platform owners' time inconsistency. Financing investment with fees charged on users reduces the investment inefficiency at the expense of user participation and token demand. Beyond the main focus on token-financed platform development, our paper provides broad implications of dynamic token allocation for token price, user adoption, stablecoins, among other issues.

## Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jfineco.2021.10.002.

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<sup>32</sup> When fees are set by centralized platform owners, they are relatively stable, as we see in IBM Blockchain's flat fee for IBM Cloud, for example, see <https://cloud.ibm.com/docs/blockchain?topic=blockchain-ibp-saas-pricing>. Fee setting on permissionless, decentralized platforms has traditionally been linked to network congestion and service capacity, which are outside our model but discussed in Basu et al. (2019) and Cong et al. (2021).

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