

In Search of Rube Goldberg Capital under Unconventional Monetary Policy

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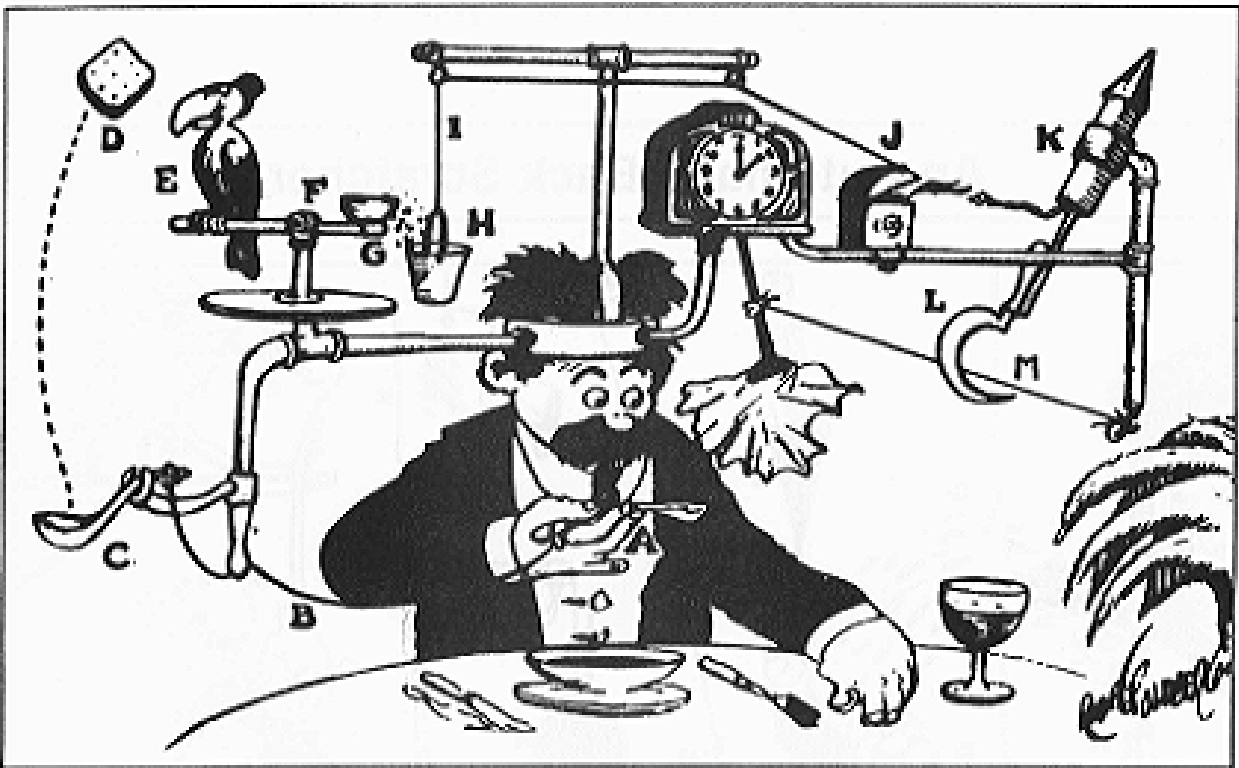
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Professor Butt and the Self-Operating Napkin (1931)

Self-Operating Napkin



A Rube Goldberg machine, named after American cartoonist Rube Goldberg, is a chain reaction-type machine or contraption intentionally designed to perform a simple task in an indirect and (impractically) overly complicated way. (From Wikipedia)

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Abstract

In his classic the *General Theory*, Keynes argued that more roundabout production methods were not necessarily more efficient and capital intensity of the best production methods would be finite at zero interest rate. The US unconventional monetary policy provides a “natural laboratory” to explore if Keynes is right or wrong. The capital-productivity trend during 1985-2021 is characterized by a vintage growth model and the “technical progress function” is empirically found to shift downward after 2008 when interest rates were close to zero or even negative. Because of uncertainty about quantitative easing, firms held buffer-stock money and postponed investment in the newest capital goods. Induced by negative interest rates, firms increased capital-intensity but not in the most efficient capital goods. Thus, the regime of unconventional monetary policy saw a trade-off between monetary stability and economic growth.

Keywords: Buffer-stock money; Capital productivity; Technical progress; Unconventional monetary policy; Vintage growth model; Zero lower bound

JEL Classifications: E22, E43, E52, O47, B22

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I. Preamble

It has been argued that the post-war mainstream macroeconomics is labour-based rather than capital-based (Garrison 2002). A reason for the evolution of macroeconomics into the current state of being largely labour-based is highly understandable given the ordeal of the Great Depression and the subsequent Keynesian Revolution, not to mention that unemployment has important economic and social impacts even without drastic economic downturns. Another plausible reason is that capital theory is one of the, if not the only one, most controversial topics in economics because of the various difficulties in resolving the related problems and issues. There have been heated, and largely unresolved, debates in the literature on capital theory, which involve a plethora of issues and problems, ranging from paradoxically simple questions, such as the definition of capital, to more conceptual, sophisticated and technical questions, like how to aggregate and measure capital when capital is heterogeneous, whether an aggregate production function exists or not, and so on. The most well-known example in the literature is probably the Cambridge-Cambridge Controversy.¹ Despite these difficulties and controversies, more theoretical and empirical studies are certainly needed in order to have a better understanding of capitalism.

Against this background, this study focuses on only one aspect or issue in capital theory in order to make the scope of this study manageable and, more importantly, to avoid opening a can of worms. More specifically, this study will explore an issue related to the level of interest rate and capital intensity in production. A “conventional” or mainstream view has that given the available technologies a reduction in the interest rate would affect the choices of production techniques and favour more capital-intensive methods. An underlying assumption or “belief” is that more capital-intensive production processes, already-known or discoverable, will always be cheaper in terms of unit production costs (excluding depreciation and interest cost) and hence more profitable than the less capital-intensive methods whenever the interest rate falls.

¹ It is not possible to go into the extensive literature here because of limited space. Nonetheless, Ferguson (1969) provides a good summary and account of the main issues from the neoclassical views of Cambridge, USA, and the criticisms from Cambridge, England.

In his classic the *General Theory*, Keynes (1936, pp. 217-221), however, argued that there was no general reason why the above view must be correct. Like Wicksell and some earlier economists, Keynes argued that increases in the capital intensity of production may cease to reduce the unit production costs beyond a certain point. He further argued that, at zero interest rate, the best methods of production would not be those of infinitely high degree of capital intensity; and beyond the point of preferred finite degree of capital intensity, more capital-intensive methods would require a negative interest rate (or subsidy) for them to be adopted by firms. Rube Goldberg was a well-known American cartoonist, whose specialty in his cartoons was the invention of highly capital intensive but obviously highly inefficient and costly methods of accomplishing simple tasks.² In this sense, Keynes implied that at some point the economy could further increase its capital intensity only by turning to Rube Goldberg machines.

The debate above is not only a theoretical but also an empirical one. A main objective of this paper is to empirically explore whether Keynes's abovementioned idea is right or wrong. The unconventional monetary policy introduced by the US Fed following the Global Financial Crisis (GFC) provides a "natural laboratory" to explore the above issue empirically. During most of the time of the regime of unconventional monetary policy during 2009-2021, most interest rates dropped to record low levels in recent decades. If we use, for the sake of simplicity and convenience, the Fed Fund rate as a proxy for the interest rate of the US economy, it plummeted to the zero lower bound (ZLB) or even became negative in real terms, whereas there was a global trend of capital deepening – increases in the capital-labour ratio -- simultaneously. Under the mainstream view, the lower interest rate during this era of unconventional monetary policy would have induced more capital-intensive production methods or processes and would consequently lead to higher productivity over time. In contrast, if Keynes is right, the lower interest rate would have induced firms to invest in more capital-intensity methods but they would not enhance productivity since they were not necessarily the most or more efficient methods, or there would even be a decline in productivity if the capital intensity had exceeded the point of minimum unit production cost.

² As can be seen from the cartoon picture "Professor Butt and the Self-Operating Napkin" reproduced above.

When asked by Alice, Humpty Dumpty said, in a rather scornful tone, “when I use a word, it means just what I choose it to mean – neither more nor less.” Unfortunately, the term capital in the economics literature can be rather slippery as economists may mean different things or ideas when they use the word. With a broad brush, Hicks (1974a) painted a picture by classifying economists according to their ways of conceptualizing the notion of capital into two groups -- fundists and materialists (or realists). Loosely speaking, the former group refers mainly to the Austrians (e.g., Hayek 1941) and classical writers, like Adam Smith, who view capital not as physical capital goods but as a sum of values that can be conveniently described as a fund and embodied in physical goods in different ways; whereas the latter group refers to the marginalists or neoclassicals, like Marshall and J.B. Clark, who view capital as an input factor in the production function.

To avoid confusion and controversies, we shall adopt the materialist approach by referring capital to capital goods or fixed capital (i.e., more specifically machinery or equipment or capital input in a production function) in our analysis to follow. This is consistent with the position of Keynes as a materialist because he was trained as a Marshallian at Cambridge, England, and there are no more than slight signs in the *General Theory* that he had departed from this position even though his classic was the genesis of the Keynesian Revolution. Or alternatively to use Hayek’s labels (1941), we adopt the “Anglo-American” approach to capital theory that gives emphasis to fixed capital rather than the Austrian approach that emphasizes circulating capital and non-permanence of capital goods. Another, and more important, reason for adopting the “Anglo-American” theory of capital is to make hypothesis testing empirically operational. This is largely because of the proliferation of use of production functions, notably the Cobb-Douglas production function, measurement of data, econometric estimation and hypothesis testing in the modern literature of empirical macroeconomics.

In addition to the main objective of using the US “natural experiment” of unconventional monetary policy following the GFC to explore, and if possible, to examine the empirical validity of the aforementioned Keynes’s idea about capital, this study aims at convincing the reader that the notion of buffer-stock money can be applied to explain the relationship between money and investment during the years of US quantitative easing (QE) – arguably a more satisfactory and

convincing explanation than other theoretical approaches. In the wake of the 2008 financial crisis, the teaching and professional practice of mainstream approaches in macroeconomics, notably the Dynamic Stochastic General Equilibrium (DSGE) models, was challenged and as a response macroeconomists have strived to improve these models or even contemplated a paradigm shift (see, e.g., Vines and Wills 2018, 2022, among others). The buffer-stock approach to monetary economics has in fact a long history that can be at least traced back to pre-Keynesian era, but unfortunately it has not gained popularity in the mainstream macroeconomics, especially in North America. The history of economics or economic thought, however, should not be confined to historians of economic thought only and monetary theorists should have a major role to play as well. Over the years, Laidler has reiterated (e.g., 1990, 1999, among others) that it is unwise for the discipline to forget what it previously thought it knew, for although monetary economics or macroeconomics has made progress over the years in terms of new ideas, new techniques and new results on the one hand, good ideas and useful insights are lost or prematurely discarded on the other. We will see in more detail below, the buffer-stock approach offers a convincing narrative of the changes in money and investment in the US after the GFC and the Great Recession, and, therefore, it should not be overlooked or ignored in our attempt to improve or reconstruct macroeconomic theory.

The organization of this paper is straightforward. The next section describes the vintage growth model as a theoretical basis for our model specification and empirical analysis for the US economy during 1985-2021. While the findings cannot be attributable solely to the unconventional monetary policy effects, they nevertheless identify a structural break in the relationship between capital deepening and capital productivity in 2009 after the outbreak of the GFC, followed by a decline in the rate of technical progress. We offer interpretations and explanations for these findings based on the vintage growth model and other relevant economic theories. As the formal econometric results and their interpretations of this section are at the aggregate level, Section III constructs a simple two-period model to characterize a representative firm's investment decision under uncertainty and the role of buffer-stock money. This theoretical model serves as the microfoundations to explain how and why investment and hence technical progress could be affected during the era of unconventional monetary policy. The model, the

narrative and the vector autoregression results based on sectoral balance-sheet data provide further explanations and interpretations. We discuss our findings and the policy implications in the penultimate section before the paper concludes.

II. The Empirical Analysis

2.1 Theoretical Framework for Empirical Investigation

Undeniably the American economy is such a complex system that it is difficult, if not impossible at all, to capture and explain the impacts of the US Fed's unconventional monetary policy on capital replacement and accumulation by one single model. Nevertheless, the theoretical framework for the empirical analysis in this study will be based on a vintage model of economic growth, although we shall, whenever appropriate, supplement the interpretations and explanations of the empirical findings with other relevant economic theories. There are many variants of the vintage model of growth, but to keep our analysis simple and straightforward we follow closely the models pioneered by Solow (1960, 1962), Phelps (1962) and Nelson (1964), in which technical progress is assumed to be embodied in new machines, i.e., capital-embodied or capital augmenting. Following the vast literature on economic growth, we assume a Cobb-Douglas production function with constant return to scale:

$$(1) \quad Q_t = F(J_t, L_t; A_t) = A_t J_t^\alpha L_t^{1-\alpha}$$

where L_t is labour input, J_t is the stock of capital jelly, and A_t is the well-known Solow residual or total factor productivity. In theory, A_t can be either a constant or $A_t = A_0 \sum (1 + \gamma)^t$, where γ is the rate of disembodied technical progress. For analytical tractability and for the purpose of this study, however, we suppress disembodied technical progress and also assume technical progress is embodied in capital or capital augmenting only, though in reality technical progress is embodied in labour or human capital too. The stock of capital jelly is defined as the aggregate capital stock with each machine weighted by a technical factor reflecting its newness or productivity:

$$(2) \quad J_t = \sum_{v=0}^t K_{vt} (1 + \lambda_k)^v$$

where K_{vt} is the capital stock of vintage v which is still in operation at time t , and λ_k is the technical progress factor assuming to grow at a constant rate each year, i.e., each year the new capital stock due to replacement will be more efficient by a factor of λ_k . Thus, the term $(1 + \lambda_k)^v$ is the technical

progress adjustment to convert each vintage capital K_{vt} into equivalent current unit of capital jelly. Hence, J_t can be interpreted as a measure of the capital stock in *efficiency units* after taking into consideration of embodied technical progress and depreciation of the capital equipment over time. If the capital stock itself is also growing due to net investment, then the growth rate of capital jelly is

$$(3) \quad \dot{J} = \dot{K} + \lambda_k$$

For the empirical analysis to follow, however, we have to adopt a slightly different measure of capital stock because the official data published by OECD for productivity analysis are based on productive capital stock and capital services.³ The former relates to the capacity of capital goods to be used as factors of production (e.g., trucks, computers, R&D, to name just a few) in the production process, whereas the latter are derived from an estimated productive capital stock by applying age-efficiency profile and age-price profile to account for depreciation and prices of capital goods as they age and hence to measure the volume of different vintages of the same capital good i that remains productively efficient in year t . This productive stock is expressed in terms of “*new equivalent units*” of the capital good i , and the flow of capital services from this capital good i is assumed to be proportional to the productive stock at the end of the previous period, and the proportional factor is set equal to unity for all types of capital goods. The overall value of capital services for the economy is then obtained by aggregating across all types of capital goods (see, e.g., Jorgenson and Griliches 1967, Schreyer 2003 and OECD 2009, 2021 for details). With little loss of generality, therefore, K in Equations (2) and (3) can be interpreted as the capital stock or capital services interchangeably.⁴

The Cobb-Douglas production function (1) can now be expressed as

$$(4) \quad Q_t = A_t \left[\sum_{v=0}^t K_{vt} (1 + \lambda_k)^v \right]^\alpha L_t^{1-\alpha}$$

While empirical studies in the traditional growth literature apply the above growth model to estimate the contribution of technical progress to GDP growth, our focus in this study is different. For the objective of this study, the evolution of capital productivity over time is proxied

³ These measures of capital stock and services for productivity analysis are thus different from the measures of capital stocks in the national income accounts.

⁴ This expression does not contain the depreciation rate δ because the data series compiled by OECD has already taken care of capital depreciation by the age-efficiency profile.

by the rate of change of the capital productivity index (KPI), i.e., the ratio of real GDP to capital or mathematically $KPI(t) \equiv Q(t)/K(t)$, and it can be derived from Equation (4) in a straightforward manner as follows

$$(5) \quad \dot{KPI} = \dot{Q} - \dot{K} = (\dot{A} + \alpha \lambda) + (\alpha - 1)(\dot{K} - \dot{L})$$

where a dot over a variable denotes the rate of change of the variable over time. The last term on the right-hand side of the above equation can be interpreted as the rate of capital deepening as it is the rate of change of the capital-labour ratio (KLR). Equation (5) is the specified model for our econometric estimation and analysis below.

2.2. Empirical Findings

Based on Equation (5) above, the two variables employed in the regression analysis are the Capital Productivity Index (KPI) and the Capital-Labor Ratio (KLR) downloaded from the OECD database website. They are annual data for the years 1985-2021. The sampling period starts from the year 1985 when the available data series begin, and it ends in 2021 when the US Fed announced publicly in January 2022 its plan to end its QE programs and subsequently started to carry out quantitative tightening in June of the same year. In the empirical analysis to follow, both variables are in logarithmic form.

Figure 1 shows the evolution of KPI over the period under study; there is an obvious downward trend in KPI , shown as the dotted line. It is quite apparent that KPI was below this long-term trend in the first few years after the outbreak of the GFC. The shaded area were periods during which the real interest rate was negative. Assuming expected inflation rate, on average, equal to actual inflation rate, the real interest rate is computed by the Fisher equation accordingly. To compute the real interest rate, the Fed fund rate is used as a proxy for the nominal interest rate whereas the change in GDP deflator is used as a proxy for the inflation rate.⁵ Figure 1 also shows the annual rate of change in private non-residential investment ($PNRI$), which, in contrast to KPI , was highly volatile. Despite its sharp decline in 2009, $PNRI$ started to recover against the backdrop of a long period of negative interest rates. As a result, capital deepening continued and

⁵ To make the Fisher equation empirically operational, we follow most empirical studies to use the actual realized inflation rate as a proxy for the expected inflation rate.

there was an upward trend in *KLR* (not shown in Figure 1, however).

Since *KPI* shows an obvious downward trend and *KLR* an upward trend, the data series are first tested for stationarity. The hypothesis of deterministic trend stationarity in the series can be rejected because the empirical results, not reported here for brevity, show that the residuals of regression models with deterministic time trends are non-stationary. To avoid spurious regression, we proceed with testing for stochastic trend stationarity and the unit-root test results are reported in Table 1. As can be seen, the ADF-test results indicate that the original data series in level are non-stationary but that they become stationary after first differencing. Against the backdrop of the US Federal Reserve's introduction of its QE program in November 2008 in response to the sub-prime mortgage crisis and the Great Recession, a structural change was highly likely. A visual inspection of Figure 1 suggests the possibility of a structural break circa 2008-9. As a matter of fact, our empirical findings are virtually unaffected whether the choice of the structural break was 2008 or 2009. We carried out the unit-root tests by taking into consideration the possibility of breakpoints in the data series, as structural breaks may bias in favour of the null hypothesis of non-stationarity (see, e.g., Perron 1989). Indeed, the Zivot-Andrew (1992) test results confirm a structural break in both the intercept and trend for *KPI* in 2008 and likewise for *KLR*. These unit-root test results are also reported in Table 1. Like the results without breakpoints, the original data series in level are non-stationary whereas the first-differenced series are stationary.

Based on the above empirical findings, we proceed to test if there was a long-run relationship between *KPI* and *KLR*. As the unit-root test results indicate a structural change in 2008, we would like to examine whether the long-run relationship, if any, would have also changed accordingly. The cointegration tests are first carried out with the entire sample of 1985-2021. As can be seen from Table 2, the results of the standard cointegration tests, namely the Engle-Granger cointegration test and Johansen test, are at best mixed: the former test does not reject the null hypothesis of no cointegration, whereas the latter suggests the possibility of cointegration. These tests, however, do not take structural change into consideration. Therefore, we also carry out the Gregory-Hansen (1996) test of cointegration with structural breaks. In the three possible scenarios of structural break under consideration, the results of the ADF procedure of this test all

reject the null of no cointegration. The test also finds a structural break in the years 2007 or 2008. Based on these findings and the historical development of the GFC, the year 2008 was chosen as the breakpoint. We then proceeded with the cointegration tests with the entire sample period as well as the two subsamples: the first subperiod runs from 1985 to 2008, whereas the second subperiod from 2009 to 2021. This division allows us to examine whether there existed a single long-run relationship between the two variables throughout the entire sample period and also its stability over time. Or alternatively, this long-run relationship was unstable and broke down because of the unconventional monetary policy, and if so, whether there was a different long-run relationship in each sub-period. The results (Table 2) suggest the existence of a cointegration relationship within each subperiod.

Based on these cointegration test results, we examined how the long-run relationship was altered by the structural change. Following the Engle-Granger (1987) framework, we ran the cointegration regressions and reported the long-run cointegration regression results for the whole-sample, the first and the second subperiods (Table 3), since the Gregory-Hansen test has already confirmed a structural break in 2008. The results of the canonical cointegration regression (Park 1992) are also reported and they indicate that the empirical findings are robust in the sense that the estimates are not significantly different in magnitude and virtually the same. On the surface, both the intercept and slope do not appear to be significantly different in value across the sub-samples. But the Wald test results reject the null hypothesis that the coefficients of the two regressions are statistically the same. Simply put, the initial long-run relationship for 1985-2008 had changed in the subsequent years following the Great Recession and QE. These estimation results are the implied long-run relationships between *KPI* and *KLR*.

Given the assumptions on the aggregate production function, the relationship between *KPI* and *KLR* can be transformed into a relationship between labour productivity and capital labour ratio; or roughly speaking, between economic welfare (as proxied by output per capita) and production technology (as proxied by capital intensity). The structural change thus has implications not only for the relationship between *KPI* and *KLR* but also for technological progress and economic welfare. More details on this point will be found later.

In reality, however, it is unlikely that the US economy was already in a steady-state

equilibrium and it could adjust rapidly to the unconventional monetary policy and restore to a new steady-state equilibrium and balanced growth path in a timely manner after an aggregate shock.⁶ A main objective of the cointegration regression estimation is to demonstrate that the unconventional monetary policy did cause a regime change and alter the theoretically implied long-run relationship between *KPI* and *KLR*, which in turn led to a subsequent adjustment of the economy.

Against this backdrop and for the purpose of this study, we are more interested in the evolution of the *KPI* and *KLR* in the short- and intermediate (or medium) run than their levels in the long-run steady-state equilibrium per se; and, more importantly, how the unconventional monetary policy might have affected the relationship, if any, between *KPI* and *KLR* and how these variables changed over time. By short-run growth it means the economic growth process in which the economy moves from a position of slack demand (say, due to the Great Recession) toward full employment, whereas by intermediate-run growth it can mean two possible types. First, it refers to the growth of the economy toward the long-run equilibrium through capital deepening and capital widening. On the other hand, it can be the case in which the economy moves from an initial long-run equilibrium growth path to a new long-run equilibrium growth path. This is what Hicks (1965, 1973) called traverse. Needless to say, the above short-, intermediate- or long-run definitions or distinctions are conceptual for theoretical analysis and these growth processes are in general inseparable in reality.

As a point of departure to find out the dynamic relationship between *KPI* and *KLR* during the period under study, we first ran a regression based on the specification derived as Equation (5), i.e., the percentage change in *KPI* was regressed on the percentage change in the *KLR* (which are empirically proxied by $dKPI$ and $dKLR$ respectively). Instead of running the regressions with two separate subsample periods, we pooled the data together and allowed both the intercept and slope to differ across the subperiods so as to incorporate the structural change in 2008. As can be seen from Table 4, based on a number of criteria such as the signs, magnitude, and statistical significance of the coefficient estimates, the goodness-of-fit and the various residual tests, the

⁶ Moreover, the conventional thinking in the growth-theoretical literature has that long-run economic growth and steady-state equilibrium are compatible with Harrod neutral technical progress but not with Solow neutrality.

empirical results can be judged to be quite adequate.

Note that a technical progress function --- a general relationship between the growth rate of output per capita ($y=Y/L$) and the growth rate of capital per head ($k=K/L$) --- can be obtained from a theoretical growth model (e.g., Kaldor 1957). In the special case of a Cobb-Douglas aggregate production function with constant return to scale, the technical progress function is a simple linear function between these two variables as follows

$$(6) \quad \frac{1}{y} \frac{dy}{dt} = \alpha_0 + \alpha \frac{1}{k} \frac{dk}{dt}$$

where α_0 is the intercept, which captures the rate of technical progress λ_k .⁷ Based on the empirical specification Equation (5), it is straightforward to show that the slope of the technical progress function, i.e., Equation (6), is simply the slope in Equation (5) minus one. Therefore, we can compute the technical progress functions for the two subperiods based on the above relationship and the estimation results for the two subperiods reported in Table 4. As can be clearly seen from Table 5, both the intercept and slope of the technical progress function had declined in the second subperiod of 2009-2021 following the structural change in 2009. The slope of the technical progress function, α , had declined from 0.3227 for the first subperiod to 0.2724 for the second subperiod.

The decline in α can be due to many reasons. Note that in the neoclassical theory of production and distribution, α is theoretically a constant as far as production technology is concerned because it is the output elasticity of capital in the case of Cobb-Douglas production. It is also the share of capital in national output according to the neoclassical theory of income distribution, i.e., factor prices are paid according to the marginal products of the input factors in perfectly competitive markets. But the empirical validity of the neoclassical theory of income distribution is highly controversial and questionable as markets are not necessarily perfectly competitive in practice, especially when the interest rate was artificially brought down to record

⁷ To my best knowledge and according to the Uzawa Growth Theorem (Uzawa 1961), the Cobb-Douglas production function with constant return to scale and Harold neutrality is the only one that yields a linear technical progress function. Difficulties arise in generalizing to other forms of production function and assumptions. For example, a CES production function will give a nonlinear technical progress function; or if the technical progress function of a production function is restricted to remain linear, then the coefficients will be time varying. All these cases require application of advanced methods like nonlinear econometrics, which is beyond the scope of the current study. Against this background, we have to leave the robustness checks of alternative production functions to future research.

low levels by the Fed rather than driven by market forces during the period under study. In brief, there is no compelling reason to maintain the hypothesis or assumption of constancy of α .

One possible explanation in the literature for the non-constancy of α , or factor shares, is short-run cyclical variations, say, due to unemployment or underutilization of input factors.⁸ This appears to be a satisfactory explanation in view of the Great Recession of 2009. Nevertheless, we shall put forward here an alternative explanation that is more relevant to the theme of investment and capital accumulation. The two explanations or hypotheses are, however, complementary rather than mutually exclusive.

Our explanation is based on uncertainty and firms' liquidity preferences. According to Keynes (1936, 1937a), the essential importance of liquidity is that individuals choose deliberately to operate inside the boundary of their individual capabilities because, given any uncertainty, it might be wise to leave a little room for error or for the unexpected; and one would operate on the boundary only if one was absolutely certain about the future.

To illustrate, consider the Cobb-Douglas production function, $Q = AK^\alpha L^{1-\alpha}$, where α is a constant representing the output elasticity of capital, the analytical framework is essentially static and atemporal, and also capital is homogenous. It follows that output elasticity = $MPK/APK = \alpha$, which is a parametric constant when capital is fully utilized.⁹ Even though the production function for each vintage of capital equipment is characterized by the same Cobb-Douglas production function, capital goods of different vintages are technically heterogeneous because of different productivity. When productivity improvements are embodied in capital equipment, one can obtain an aggregate production function in the form of Cobb-Douglas as in a vintage growth model, $Q_t = A_t J_t^\alpha L_t^{1-\alpha}$, as shown in Equation (1). Output elasticity of capital is a constant when the capital jelly stock J_t is measured in efficiency units up to time t and also it is fully utilized. But output elasticity may no longer remain constant when capital goods of older vintages (hence less efficient) are used instead, or the capital jelly stock is not fully utilized, or both. To illustrate, suppose for some reason the actual capital jelly stock in use is less efficient or less productive than

⁸ For example, when the economy operates below the full-employment level, the labour share of income will increase whereas that of capital will decrease, and vice versa for the case of above the full-employment level.

⁹ Simply put, the economy is always operating on the production function – as output above the production function is technologically infeasible, whereas output below implies unemployment or operational inefficiency.

it would otherwise be, such that $Q_t = A_t [\kappa J(t)]^\alpha L_t^{1-\alpha}$, where $\kappa < 1$. It is easy and straightforward to show that output elasticity of capital in this case is $\kappa^\alpha \alpha < \alpha$. The economic intuition is also straightforward: given the available technologies, say, if an increase in one unit of the most efficient machine (or by one percent assuming there are initially 100 of these machines in operation) would lead to an increase in output by α percent, then an increase in one unit of a less efficient machine would naturally lead to an increase in output by less than α percent.

Theoretically, this explanation is in line with Keynes's notion of liquidity under uncertainty. Firms would invest in the most efficient capital goods available only if they were certain about the economic outlook; and when the degree of uncertainty increased, they would choose a more conservative investment strategy to maintain a liquid position (see further elaboration in Section III below).

Empirically, given the global trend of increasing capital intensity, notably in the second subperiod during which there was a high degree of uncertainty because of the unconventional monetary policy, a lower α may thus suggest a higher capital stock but with lower productivity. Perhaps what is more interesting is the lower intercept of the technical progress function in the second subperiod. If we assume technical progress is embodied in capital goods only (i.e., $\dot{A}=0$) then it is straightforward to compute λ_k from the estimated intercept and slope according to Equation (5). As can be seen from Table 5, the rate of technical progress had also declined slightly from 0.02131 (or 2.13% p.a.) in the first subperiod to 0.02077 (2.08% p.a.) in the second subperiod. The difference in the rates of technical progress is seemingly small, plausibly because of the rise of relatively more productive intellectual property products (e.g. computer software) than physical equipment over time.¹⁰ but even small difference in growth can translate into large differences in living standards over time. More importantly, these findings suggest that by pushing interest rates downward towards the ZLB or even to the effect of a negative real interest rate, the unconventional monetary policy was able to revive investment, as indicated by the growth rate in *PNRI* and continued capital deepening, but the policy, at least on the surface, failed to

¹⁰ According to the US Fed's financial accounts, the value of equipment held by non-financial corporate businesses was 4.55 times the value of its holding of intellectual property products in 1985.Q1. The ratio dropped to 2.35 in 2007.Q2 before the Great Recession and further to 1.74 in 2021.Q4.

promote technical progress by inducing firms to invest in capital goods of the newest vintage and highest productivity.¹¹

2.3 Induced Technical Progress

How did the unconventional monetary policy induce technical progress? The technology of an economy at a certain time is defined as a collection of all the known usable techniques at that time. A technique of production is described by specifying the amount of capital necessary at the beginning of a period to equip one unit of labour, the amount of output produced at the end of the period, and the rate of depreciation of the capital during the period.

The lower interest rates due to QE, all other things equal, would in theory induce higher investment because certain unprofitable investment projects at higher interest rates previously could become profitable at lower interest rates. At the same time, the lower interest rates would change the ratio of factor prices and hence induce firms toward choosing relatively more capital-intensive production methods because of lower user costs of capital.

Even though technical progress in our vintage growth model is capital augmenting, it is not necessarily capital saving. For Solow (2008) correctly reminds us that labour-augmenting inventions are not necessarily labour saving. Such inventions increase the marginal product of a natural unit of labour, but they also increase the ratio of the effective labour to capital and hence increase the relative marginal product of capital; and the net effect depends on the elasticity of substitution.

In theory the elasticity of substitution should be equal to one under the assumption of a Cobb-Douglas aggregate production function, but it can in reality differ from unity because capital is not putty-putty but putty-clay in the actual production. To capture firms' choices of techniques and the technical changes during the period under study, we take a further look at the data and

¹¹ But care should be given to this finding and interpretation because they are based on econometric results alone as well as the underlying unrealistic assumption of embodied technical progress. For it could be the case, though highly unlikely, that λ_k increased in the second subperiod but the rate of disembodied technical progress decreased to such an extent that the intercept of the technical progress function decreased as a result. A more likely scenario is that both the rates of embodied and disembodied technical progress decreased in the second subperiod. Unfortunately, we are not able to disentangle the two rates unless we extend our current analytical framework or we have auxiliary information from other studies.

empirical findings in an attempt to draw inference about the labour productivity (measured by the output-labour ratio or *LPI*) and capital productivity (*KPI*). Recall from the Cobb-Douglas production function and technical progress function that for given values of *KPI* and *KLR* they imply a corresponding *LPI*. Each pair of *KPI* and *LPI* for a given year can be regarded as the hypothetical growth-distribution schedules for the US economy for that year.¹² A purely labour-saving technical progress corresponds to a rise in the *LPI* while *KPI* remains unchanged, and vice versa for a purely capital-saving technical progress. Technical progress is factor-saving when both *LPI* and *KPI* increase.

As already mentioned, the OECD data show a global downward trend in capital productivity on the one hand and a global upward trend in capital deepening on the other. For brevity, we do not look into how the shifts in the growth-distribution schedules over the entire period under study. It suffices for our purpose here to look into the following years. In 1985, the first year of the period under study, *KPI* stood at 149.2 whereas *KLR* or the capital deepening index was 42.3; therefore, the implied index for output per labour or *LPI* was 63.1. In 2008, the year prior to a structural change due to the GFC and the introduction of QE, the values for *KPI*, *KLR* and *LPI* were respectively 107.4, 86.8 and 93.2, whereas they were 95.6, 112.7 and 107.7 in 2021. These figures show that the technical progress was not factor-saving; it was capital-using and labour-saving over time. It is not surprising at all as the downward trend in interest rates could mean a tendency for the price of capital services to fall relative to wage rates and thus induced a bias toward labour-saving technical progress or inventions. The tendency toward using more capital services relative to labour is evidenced by the upward trend in *KLR*. What is perhaps more interesting is how the trend of capital deepening affected labour productivity -- the implied *LPI* increased at a rate of 1.71% a year over the years 1985-2008, but it increased at a noticeably reduced rate of marginally lower than 1% a year during the years of unconventional monetary policy. Perhaps we can liken these findings to this instance: plowing with a machine tiller raises a farmer's productivity and yield when compared with plowing by hand; but many machine tillers may not be as productive as one tractor!

¹² Alternatively, these schedules are also the real wage-profit rate schedules commonly used in the literature (see, e.g., Hicks 1965). The envelope of the growth-distribution schedules is the efficiency frontier.

III. Buffer-Stock Money and Investment Under Unconventional Monetary Policy

Can the above empirical findings of capital intensity and technical progress at the aggregate level be explained in terms of microfoundations? To explain how and why investment and hence technical progress could be affected during the era of unconventional monetary policy, a simple two-period model is constructed to characterize a representative firm's investment decision under uncertainty and the role of buffer-stock money.

Hicks (1974b) challenges us economists to achieve a deeper and more integrated view of the relationship between investment and money demand than in his original IS-LM model (Hicks 1937). Not only the two-period model below is an attempt in this direction but also it offers another perspective to explain and interpret the above empirical findings. Our approach is, however, both theoretical and narrative. As Sir John Hicks maintains, economics "if it is on the edge of science ...[it] is also on the edge of history" (Hicks 1979, p. 4).

3.1 A Simple Two-period Model of Investment under Uncertainty

To begin with, consider a "representative" firm or entrepreneur who has to decide today ($t=0$) to invest in capital goods to produce output over two periods, which can perhaps be simply called respectively short run and longer run (not long run, for fear that in the long run we are all dead! (Keynes 1923)).¹³ Let us put

$$(7) \quad Q_1 = \sum_{t=1}^T \frac{q_t}{(1+r_t)^t}$$

where $\tilde{Q}_1$ is the total output over the short run and $q_i, i=1,2,3,\dots, T$, are the output in each i th subperiod (say, quarterly output) during the short run, and r_t is the interest rate.¹⁴ Analogously, we can define an equation in terms of $\tilde{Q}_2$ for the longer run after T . To capture output uncertainty

¹³ Needless to say, our terminology tries to echo short-period and long-period analysis of Marshall or Keynes. But admittedly there are lots of subtleties for us modern economists to explore in the works of Keynes and other earlier writers, like Hicks, the Austrians and the Wicksellians (see, e.g., Hicks 1985) who adopted period analysis rather than technically more advanced methods like dynamic programming and alike. As Leijonhufvud (1968) argues, Keynes's attempt and emphasis on processes and information flows within the economic system has been rejected or even unrecognized by the neoclassical synthesis that has forced Keynes's ideas into a static general equilibrium system of simultaneous equations. We do not address the history of thought and methodological issues here, however.

¹⁴ For reason given in the next footnote, the general price level and inflation (both actual and expected) are not incorporated into this model and therefore the nominal and real interest rate are treated to be equivalent, at least in the short run.

over time, the q 's are assumed to be random variables and hence so are the $\tilde{Q}$'s.¹⁵ The output uncertainty, of course, includes the potential impact of monetary policy on output. Like Knight (1922), Keynes (1921, 1936) made a distinction between genuine or radical uncertainty and risk; and his view of the future as dark and uncertain is the mainstay of his liquidity preference theory of money demand. Although Keynes believed that certain propositions were so uncertain in principle that they were incapable of having possessing a numeral value in terms of probability laws, his conception of probability in general is epistemic – *a priori* probabilities are degrees of belief in some propositions given one's information.¹⁶ Here we follow an eclectic approach like Makowi (1989) to define uncertainty not as Knight-Keynes genuine uncertainty but as situations involving risk plus the possibility of learning and utilizing new information if economic agents postpone their decisions.¹⁷ Accordingly, the firm or entrepreneur is assumed to have subjective probability distribution about the random variables $\tilde{q}$ and $\tilde{Q}$.

For simplicity, the assets under the firm's portfolio choice are assumed to be (i) noninterest bearing money and (ii) capital goods consisting of two kinds, namely current and new machines. With reference to the vintage growth model, by a current or existing machine we mean one that embodies the current production technology already in use; it is assumed to have a life of T , a purchase price of P_{ke} today and a unit operating cost of C_e per unit of time. In contrast, by a new machine we mean one that embodies the newest technology to be introduced; it is assumed to be more durable and more efficient such that it has a longer life covering the two periods and a lower unit operating cost $C_n < C_e$, but a higher purchase price $P_{kn} \geq P_{ke}$.¹⁸ For simplicity and analytical

¹⁵ For analytical tractability, price of the output, and hence inflation, is suppressed in our model or normalized to one in each period t . Incorporating price uncertainty as another random variable into our model will make the mathematical manipulations more tedious than necessary, as it involves the products and quotients of random variables. To bring out the basic message and conclusion of our theory, we therefore follow the KISS rule in modelling: keep it simple and straightforward.

¹⁶ Bateman (1987) offers a clarification of Keynes's conception of probability as well as a refutation of other economists' misinterpretation of Keynes.

¹⁷ This approach is more or less for the sake of intellectual discourse and knowledge dissemination. On the one hand, the current state of mainstream macroeconomics will most likely find it difficult to accept the centrality of radical uncertainty à la Knight or Keynes. On the other hand, radical uncertainty is difficult, if not impossible at all, to model mathematically or probabilistically because it arises from our imperfect and incomplete knowledge – i.e., the unknown unknowns or our ignorance.

¹⁸ This assumption that the current machine has a shorter life than the new machine can be relaxed without affecting qualitatively our theoretical findings. See below for the cases in which the two machines have the same life. What is

tractability, the purchase prices and unit operating costs are assumed to remain unchanged over time.¹⁹

We further assume that the firm's objective is to maximize its expected profit by deciding today to invest or not; and if invest, it has to choose either a current machine or a new machine. In either case, the investment decision is irreversible. According to Keynes (1936, Chapter 12), expectations play a crucial role in the choice of entrepreneurs between purchasing new or existing capital goods, or to postpone investment by purchasing or holding financial assets (or money in our simple model here). Based on subjective expectations and information available, the firm chooses to invest in the new machine today if the expected profit

$$(8) \quad E(\Pi_n) = [E(\tilde{Q}_1) + E(\tilde{Q}_2)](1 - C_n) - P_{kn}$$

exceeds a certain required profit level, say Π^* .

Alternatively, the firm can choose to invest today in the current machine and then, at time T, (i) replace it with another current machine, if necessary (say, unexpectedly the first machine becomes obsolete)²⁰ or (ii), to buy a new machine. In this setting, investing in the current machine today offers the firm flexibility and advantage; if at time T, the firm realizes that the current machine is not obsolete, its decision choice is then between the continued use of the current machine or to buy a new machine. In this case, the firm will not buy the new machine if $[(C_e - C_n)E(\tilde{Q}_2)] < P_{kn}$; or in words, the expected saving in the operating cost is lower than the purchase price of the new machine. Note that in this case the firm can have the advantage of revising its expectation about $\tilde{Q}_2$ with information received up to time T.

With information available today, the expected profit under this investment strategy will

crucial is that the current machine is relatively more liquid than the new machine for one reason or another, say, the existence of a secondary spot market in practice.

¹⁹ Admittedly these assumptions are unrealistic. For example, the unit operating cost of a machine will not remain unchanged over time when the machine ages because of wear and tear or obsolescence. Relaxing this unrealistic assumption, however, will involve another extensive literature on the replacement of equipment. It suffices for our purpose here that $C_n < C_e$ (or in words, the current machine is operational inferior to the new machine) even though the operating costs of both types of machines will change over time. Likewise, the purchase prices will change over time but it suffices as long as $P_{kn} \geq P_{ke}$.

²⁰ If today the firm expects the current machine will not become obsolete at time T, then the firm's decision choice is straightforward to compare the expected profit of investing in the new machine, i.e., Equation (8), with that of investing in the current machine, i.e., the counterpart of Equation (8) with the appropriate changes in the subscripts of the variables.

be

$$(9) \quad E(\Pi_e) = E(\tilde{Q}_1)(1 - C_e) + E(\tilde{Q}_2)(1 - C) - P_{ke} - \frac{P_k}{(1+r_T)^T}$$

In the above equation, $P_k = P_{ke}$ and $C = C_e$ if the firm replaces its current machine with another one after time T , and $P_k = P_{kn}$ and $C = C_n$ if it purchases a new machine instead. In any case, it will be more profitable to invest in the new machine if $E(\Pi_n) > E(\Pi_e)$ or

$$(10) \quad P_{kn} \left(1 - \frac{1}{(1+r_T)^T} \right) - P_{ke} < E(\tilde{Q}_1)(C_e - C_n)$$

and vice versa. But if $E(\Pi_n)$ or $E(\Pi_e) < \Pi^*$, the firm will postpone investment and hold money instead. Postponing the commitment of making irreversible investment can be desirable if arrival of information is able to make the deferred investment more valuable or profitable in the longer run and sufficient to offset the short-run loss due to inaction. Simply put, under uncertainty there is an option value associated with avoiding irreversible investment (see, e.g., Bernanke 1983, Abel et al. 1996, to name just a few, who have made this argument by using different approaches or viewpoints).

Our simple model does not make use of the notion of option value, but it is essentially the same in that under uncertainty it can be desirable for the firm to maintain a more liquid position by holding money rather than to become less liquid or illiquid by committing to irreversible capital investment. The importance of liquidity preference to investment decisions have long been recognized.²¹ When firms make real investment in plant and machinery because of replacement or expansion, they take up less liquid positions by giving up more liquid assets (say, reserve assets like money or short-term securities) for long-term capital goods. There is substitutability between these more or less liquid assets.²² Such investment is not only risky but also not easily reversible

²¹ For instance, Keynes devoted an entire chapter in his classic (1936, Ch. 15) to discuss the important role of liquidity in the inducement to invest. Keynes also described in his earlier work (1930, pp. 140-1) how the wealth holder can hold wealth in the form of money (or the liquid equivalent of money) or in other forms of loans or real capital.

²² For the purpose of our study, our model includes only money and two kinds of capital goods. Hicks (1967) offer a broader and more general analytical framework in which the total assets – both real and financial -- in the balance sheet of a manufacturing firm are classified into running assets, reserve assets and investment assets. On the real asset side, plant and machinery in use are running assets, whereas some equipment, machines and the like, are reserve assets and will come into use only in the event of a need for repairs or emergency. On the financial side, money is without doubt a running asset (i.e., the transaction motive of Keynes), but money can also be held as a reserve asset (precautionary motive) and an investment asset (speculative motive).

in general because of transaction costs. In a world of uncertainty, it is conceivable that firms might prefer to hold money for precautionary motive or as buffer-stock money and postpone their real investment projects instead until uncertainty subsides or it is resolved, or more relevant information is available. Money is thus similar to a buy option that allows its holder to purchase an investment project later when deemed desirable. The buffer-stock approach to monetary economics has existed for a long time, though it has not gained dominance in the mainstream (see, e.g., Carr and Darby 1981, Laidler 1984, Milbourne 1988, and Goodhart 1989, among others). In a nutshell, the underlying basic idea of the buffer-stock approach is based on the precautionary motive for holding money of Keynes (1936) and Friedman's idea that money is a temporary abode of purchasing power (e.g., Friedman 1956, Friedman and Schwartz 1963). When there is uncertainty about income and expenditure flows or unanticipated shocks, and also when economic agents cannot adjust instantaneously to restore equilibrium because of adjustment costs or transaction costs --- say, the gathering and processing of information are costly and take time, or price stickiness --- they thus tend to hold money as buffer stocks to absorb the unanticipated shocks, to meet the discrepancies between expenditures and receipts, or to mitigate the consequences of making mistakes in their economic decisions, and so on. While most of the studies on the buffer-stock approach focus on stability of the money demand, it is also relevant to other macroeconomic issues and may be able to offer better explanation than other approaches because it allows the economy to be out of equilibrium, at least temporarily, in the transmission mechanism. Among the four approaches to buffer stock models surveyed by Milbourne (1988), the Type II Models (e.g., Laidler 1984) feature a kind of Keynesian short-run stock and flow disequilibria. It is highly relevance to our case here: the US Fed's QE caused a temporary disequilibrium in the money market, and the artificially low interest rate due to the unconventional monetary policy meant that the goods market was also out of equilibrium as savings did not equate investment. This will be elaborated below very shortly.

Now returning to our theoretical model, it can be desirable for the firm to invest in the existing machine rather than the new machine because the former investment is more liquid than the latter even though the new machine has a lower unit operational cost. This is because even if the expected profit for the first period from investing the new machine based on the information

available today is higher than that from the current machine, this may not continue to be the case in the second period when there is arrival of news or shocks. In contrast, investing in the current machine today allows the firm to maintain a relatively more liquid position, and it has the opportunity to update its expected profit for the second period by a new information set at time T, say, by observing the evolution of the output q 's during the first period and hence a more accurate prediction of $\tilde{Q}_2$, and then to decide which machine to choose accordingly. For example, if output growth in the first period suggests the growth trend will continue into the second period, the expected profit will be higher by investing in the new machine.²³ But if the expected profits from investing in either machine are so uncertain and pessimistic that the firm may find it more desirable to simply defer its investment and hold money instead until a more profitable timing arises later.

In addition to the above theoretical analysis, institutional settings in the real world also reveal that new machines are less liquid than current machines. Capital goods are primarily held for their anticipated ability to produce income in the future more than as stores of values. Some capital goods are custom-built or ordered and placed on an individual contract basis because of the specific nature of certain aspects of fixed capital. This is notably the case for newly introduced machines, and as such they are highly illiquid because of absence of a secondary market. And even if such a spot market exists, it is poorly organized. By contrast, existing machines may have similar characteristics like new machines, but they are relatively less illiquid because they can be purchased more or less off the shelf or from the secondary markets for second-hand capital goods. As these secondary markets are not so well organized as markets for financial assets, the current machines are still not very liquid.

The Keynes-Hicks generalized liquidity is related to not only uncertainty or risk but also economic agents' risk attitude. In the above scenarios, it is assumed that the firm is risk neutral. But if the firm is risk-averse, not only the mean but also the variance of the profits has to be taken into consideration in the investment decision. It is straightforward to show that the variance of the profit from investing in the new machine is higher than its counterpart for the current machine.

²³ It can be argued that the above analysis and predictions are based on the assumption that the new machine is less liquid than the existing machine because of the difference in their life. But our results are qualitatively unaffected even if this assumption is relaxed. If both machines have the same life and the relevant period is from today up to time T, the new machine will be preferable if $P_{kn} - P_{ke} < E(\tilde{Q}_1)(C_e - C_n)$ as long as $E(\Pi_n), E(\Pi_e) > \Pi^*$.

Take the simple case in which the two machines have the same life as illustration. We have

$$(12) \quad Var(\Pi_n) = (1 - C_n)^2 \sigma_{Q_1}^2 > Var(\Pi_e) = (1 - C_e)^2 \sigma_{Q_1}^2$$

This result that new machine is riskier (in terms of profit variability) than current machine is derived from simple mathematical and statistical manipulations based solely on our model specification and assumptions. As a matter of fact, new technologies or processes are risky and their chances of success are usually low. Depending on the firm's utility function, there is a trade-off between expected profit and risk. Investing in new machine may not be optimal if the higher expected profit is not enough to compensate the higher risk exposure.

A more interesting case, and also highly relevant to explaining the investment behaviour observed during the Great Recession, is one in which the risk-averse firm makes the investment decision based on the safety-first principle (e.g., Roy 1952). To illustrate, let us suppose the firm's equity capital is $\mathcal{E}$ and the firm avoids making an investment that would jeopardize its survival. By applying the well-known Bienayme-Chebycheff inequality in probability theory, the probability of bankruptcy, Pr , is given by

$$(13) \quad P_r(\Pi < \mathcal{E}) \leq \frac{\sigma_{\Pi}^2}{(E(\Pi) - \mathcal{E})^2}$$

The current machine is thus preferred to the new machine if investing in the former has a lower probability of bankruptcy. One of the many possible cases, for example, is when both production methods are able to generate the same expected profits (i.e., the same denominator in the above equation) but the profit variability is higher by using the new machine.

The above model is the microfoundations. At the aggregate level, firms' decisions on investing in the current or the new machines and the relative shares affect the stock of capital jelly as defined by Equation (2), as the aggregate capital stock with each machine weighted by a technical factor reflecting its newness or productivity. The rate of technical progress will thus be affected accordingly.

3.2 Further Explanations and Interpretations of the Empirical Findings

The regression results reported in the previous section are based on a vintage growth model at the aggregate level. We can now apply the above two-period model as well as the notion of buffer-

stock money as the “microfoundations” to supplement and further explain our regression results, particularly the aggregate private non-residential investment (*PNRI*) behaviour observed during the years of unconventional monetary policy.

The term “unconventional” might have induced firms to interpret or misinterpret that the Great Recession would be deeper and last longer than a normal recession. They were probably also highly uncertain about the effectiveness of this unconventional monetary policy QE1 in reviving the economy, at least initially.²⁴ Firms’ investment decisions, according to our model as well as the conventional economic theories, depend on their subjective expectations about future output and profits.²⁵ Even though the lower interest rate due to QE would theoretically increase the demand for capital goods as a result of lower user cost of capital and higher quasi-rent of capital goods, the increase was offset by the decrease in demand induced by an expected sharp decline in output. Consequently, firms held back their replacement investments, let alone investments for expansion or innovative investment.

Indeed, when quantitative easing (QE or QE1) was initiated on November 25, 2008 following the GFC, there was a high degree of economic and financial uncertainties or instability, as reflected by the Chicago Board Options Exchange Volatility Index (*VIX*) --- a popular measure of the stock market’s expectation of market volatility --- depicted in Figure 2, due to the economic recession and the Fed’s unprecedented unconventional monetary policy. A rise in the *VIX* means increased fear and risk in the market, whereas a drop suggests more market stability. A *VIX* index value of 15 and below indicates low volatility and a certain amount of market optimism, whereas a value of 15-25 indicates a certain amount of volatility, though not extreme, and a value of 30 or above indicates high market volatility. As can be clearly seen from the behaviour of the *VIX* in Figure 2, the market was highly volatile and uncertain during the period from the second half of 2007 to the first half of 2012. In other words, the uncertainty triggered by the GFC and QE lingered on for years.

²⁴ It was not unreasonable to cast doubt on the effectiveness of QE in boosting output, as reflected by Japan’s experience with QE during its lost decades since the 1990s (see, e.g., Koo 2009).

²⁵ According to Keynes’s theory of capital and investment, for example, the marginal efficiency of capital (MEC) schedule would shift downward following the GFC and hence a decline in investment. Similarly, the neoclassical theory of investment would predict a decline in the desired capital stock and hence investment accordingly.

As formally derived by Jones and Ostroy (1984), when uncertainty is high, economic agents' desire for flexibility is high as well. Accordingly, firms' desire for investment in irreversible projects will be temporarily low, and their desire to hold money for precautionary motive will be high so as to maintain liquidity. This explains the sharp decline in private nonresidential investment in 2009 as observed in Figures 1 and 2. If in general firms' outlook following the outbreak of the GFC was so pessimistic that their expected profits dropped below Π^* , most, if not all, of them would prefer to hold money balances and defer their investment projects accordingly. This is reflected by the sharp decline in the level of nonresidential investment on the one hand and the skyrocketing monetary base (largely because of excess reserves held at depository institutions) on the other in 2009. As a result, the “conventional wisdom” that investment and the interest rate are inversely related simply failed to materialize in this case.²⁶

As can be seen in Figure 2, uncertainty remained high in the ensuing years, as reflected by the *VIX*, despite the introduction of QE2 in 2010 and QE3 in 2012. Firms' preferences to hold money balances rather than to invest means that the huge monetary shocks due to the Fed's QE were largely absorbed by the private sector and reflected in the sharp rise in banks' excess reserves and hence the monetary base.²⁷ Firms tended to hold back their expansion and innovation investment, and made replacement investments only when necessary, until the US economy appeared to show strong signs of recovery. By holding money balances, firms had the time and opportunities to gather and process available information to reevaluate the profitability of their investment projects. In the real world, one may argue, the private sector could hold some other default-free, highly liquid and interest-bearing assets such as treasury bills rather than money as the buffer stock. But the institutional arrangements in the real world means that money, rather

²⁶ To be fair, this “conventional wisdom” would not be held by serious mainstream or neoclassical economists either. Although the lower interest rate or user cost of capital due to QE would be likely to induce a higher desired capital stock and investment, the expected decline in GDP due to the subprime mortgage crisis had an offsetting effect. Theoretically, the net effect could not be determined a priori. But empirical evidence suggests that the scale variables (like output and sales) and financial variables (like cash flows and liquidity) are more important than interest rates in affecting investment (see, e.g., Caballero 1999). Therefore, the prediction would be in line with Keynes or our model.

²⁷ For example, corporations in all manufacturing industries had their total cash on hand and in US banks jumped sharply by 26.7% over the period Q1 2008—Q4 2009 according to data from the Fred Data Base. Similar cash increases could also be found in other sectors. In brief, both banks and the non-bank sectors increased their cash holdings.

than those short-term liquid financial assets, has to be held to satisfy the finance or cash-in-advance constraint (e.g., Tsiang 1966, Clower 1967). In addition to the transaction and precautionary motives, money is therefore preferred as a buffer because of this lesser-known fourth motive – the finance motive – for the demand for money due to Keynes (1937b), not to mention the speculative motive amid the ZLB. So even though the nominal interest rate dropped to the ZLB and became negative in real terms, *PNRI* only started to rebound gradually in response to QE1 and QE2 and it did not return to its pre-crisis level until 2012. Here the buffer-stock money fits in nicely and offers better explanation for this phenomenon of persistent uncertainty than many other approaches: “Uncertainty causes agents to hold money, but the very fact that doing so protects them from its consequences also helps to ensure that the uncertainty in question persists” (Laidler 1987).

As a matter of fact, the Fed had to implement different phases of QE through the end of QE3 in 2015.²⁸ When uncertainty gradually started to subside, as indicated by the *VIX*, firms began to reduce their buffer-stock money and started to increase investing in capital goods. As a result, *PNRI* continued to climb whereas the monetary base started to come down when excess reserves were extended out as commercial loans. This trend gathered its momentum until 2020 when the economy was hit by the COVID-19 pandemic and the Fed acted as lender of last resort and resumed QE to support the economy. This adjustment process is consistent with the general notion that when firms’ or investors’ uncertainty starts to be resolved, their desire for investment and hence demand for loanable funds will revive; and their portfolios will switch gradually over time from money into illiquid capital goods.²⁹

²⁸ For an insider account of QE, see Bernanke (2022).

²⁹ It is not necessary for us to build a formal mathematical model here to obscure the underlying economic ideas. However, this adjustment process is analogous to, though not exactly the same, as the one in the formal three-asset model of Orr (1970), which is an extension of the well-known model of precautionary demand for money by Miller and Orr (1966). In his model, a representative firm is assumed to hold three types of assets, namely, in terms of liquidity – money, a liquid earning asset (or market portfolio) and physical capital (plant and machinery). The firm minimizes the cost of managing its cash balance as there are lump sum transaction costs when one type of asset is transferred into another. Cash flows are stochastic and unanticipated excess cash balance will be dissipated first into the liquid earning asset and then the physical capital. Alternatively, for a non-mathematical exposition of the relationship between liquidity and the spectrum of assets, see Hicks (1935, 1967).

3.3 Evidence of the Buffer-Stock Money Mechanism

We employ quarterly balance-sheet data of non-financial corporate business and a bivariate vector autoregression with exogenous variables (VARX) model to test empirically the above buffer-stock mechanism. Equipment (KE) and currency and transferable deposits (CD) are respectively proxies for capital goods and money. Their current percentage changes are the endogenous variables, which are related to each other as well as their past lags and two exogenous variables – the extent of uncertainty as proxied by VIX in the previous period whereas the current change in the monetary base (MB) to reflect US Fed’s monetary policy stance. If the Fed’s monetary policy is assumed to follow a feedback rule based on *observed* aggregate activities, then current changes in the monetary base depends on predetermined variables and is unrelated to current changes in both capital goods and money held by private businesses. Alternatively, the QEs can arguably be regarded as executed at the Fed’s discretion. In either case, it is reasonable to assume MB to be exogenous for our purpose of empirical investigation. The system of structural equations is specified as³⁰

$$(14) \quad \dot{KE}_t = \alpha_0 - \alpha_1 \dot{CD}_t + \alpha_2 \dot{KE}_{t-1} + \alpha_3 \dot{CD}_{t-1} + \alpha_4 \dot{MB}_t + \alpha_5 VIX_{t-1} + \tilde{\mu}_t,$$

and

$$(15) \quad \dot{CD}_t = \beta_0 - \beta_1 \dot{KE}_t + \beta_2 \dot{KE}_{t-1} + \beta_3 \dot{CD}_{t-1} + \beta_4 \dot{MB}_t + \beta_5 VIX_{t-1} + \tilde{v}_t.$$

where dotted variables are in growth rates. For the exposition to follow, random shocks to Equations (14) and (15) are called “real shocks” and “nominal shocks” respectively.

All the variables are stationary.³¹ Table 6 reports the VARX results and the structural coefficients α_1 and β_1 under exact identification with restrictions.³² In theory, the cash-in-advance constraint suggests a temporal causal order from money to capital investment – the restriction $\beta_1 = 0$ can be imposed to form a recursive system for exact identification. However, a reverse order can also be justified by imposing $\alpha_1 = 0$, because capital goods take time to build and hence capital

³⁰ The lag-order selection test (Table 6) below also suggests one lag. After all, any higher order VAR can be recast as a first-order VAR.

³¹ For instance, the $Z(t)$ statistics for KE , CD , MB and VIX are respectively -6.08, -11.90, -9.61 and -4.31, although details of the unit-root test results are not reported here for brevity.

³² When a VAR model is exactly identified, the coefficient estimates of the lagged variables and exogenous variables are identical to their structural counterparts, though their standard errors differ. For brevity, only the VARX results are reported here.

investment committed earlier can affect current money holdings. In reality, the two cases are not incompatible. In view of this chicken-and-egg question, each of these two cases of different temporal ordering – labelled as Case I and Case II -- is estimated by structural VAR (SVARX) with the corresponding restriction.

In either case, the SVARX results indicate that $\dot{KE}_t$ and $\dot{CD}_t$ are negatively related but, as expected, their impacts differ. In Case I, a one-percent increase in CD_t would lead to a meagre 0.01% decrease in KE_t , whereas in Case II the same increase in KE_t would lead to a fall in CD_t by 4.6%. These magnitudes are not unreasonable partly because capital investment is mainly driven by factors like expected future profits more than current money balances, and partly because KE_t is much larger than CD_t as non-financial corporate businesses' assets.

The VARX findings also reveal a negative relationship between KE_t and CD_{t-1} as well as between CD_t and KE_{t-1} . On the other hand, perceived higher uncertainty in the previous period is followed by a negative $\dot{KE}_t$ but a positive $\dot{CD}_t$. These patterns are consistent with the buffer-stock notion that corporations restrain from capital investment amid higher uncertainty (thus capital stock declines as net investment is negative) and hold more buffer-stock money instead. The liquidity need is, however, to some extent relieved by QE, as reflected by the negative relationship between $\dot{CD}_t$ and $\dot{MB}_t$. The unconventional monetary policy also has a positive impact on capital investment growth.

The dynamics of the system is better grasped with visual aids. Figure 3 depicts the structural (orthogonalized) impulse response functions (IRFs). We focus on Figure 3(a) for illustration as the two cases are virtually identical. In response to a positive nominal shock, $\dot{CD}_t$ would increase immediately whereas $\dot{KE}_t$ would decline. If the shock is only transitory, $\dot{CD}_t$ will decay quite rapidly, almost within one quarter, back to a steady state of zero growth. In contrast, $\dot{KE}_t$ will dip down further in the first quarter before it recovers to zero growth over a longer time horizon. On the other hand, in response to a temporary real shock, $\dot{CD}_t$ would decrease for one quarter and then returns to nearly zero growth in the second quarter, whereas $\dot{KE}_t$ would go up immediately and the growth rate will decay and take about two years to reach a steady state of zero growth. These patterns reflect the respective liquidity and transaction costs of money and capital goods in the adjustment mechanism.

Equally relevant and important to our analysis is the dynamic multiplier functions (Figure 4). As can be clearly seen, a higher degree of uncertainty leads to an immediate increase in money balance and a simultaneous reduction in capital investment. If uncertainty is only transitory, both $\dot{C}D_t$ and $\dot{K}E_t$ will dissipate over time, as indicated by the dynamic multipliers. Under prolonged uncertainty, however, firms will continue to accumulate money balances and to shrink their capital investment over time, as suggested by the cumulative dynamic multipliers. These patterns are consistent with the predictions of our theory of buffer-stock money and investment.

During this age of high uncertainty, an expansionary monetary policy could relieve firms' money hoarding and also boost their capital investment. However, Figure 4 reveals that these dynamic multiplier effects of monetary policy would not be sustainable over time under a one-time policy; to attain the cumulative dynamic multiplier effects, the expansionary monetary policy had to persist. The latter explains why investment in capital equipment revived and grew following the US Fed's several rounds of QE over the years.

Overall, the empirical results provide evidence in support of the buffer-stock mechanism. All the coefficients have the correct signs as predicted by theory, though not all statistically significant at the conventional because of the small sample size. The major diagnostic tests indicate no major econometric problems like autocorrelation, even though the residuals of the $\dot{K}E_t$ equation are not normally distributed, mainly attributable to the sharp declines in capital investment right after the outbreak of the GFC. Admittedly, the findings are by no means definitive. Empirical analyses based on high frequency data and micro-data at the firm level are avenues for future research.

3.4 Investment during this regime of Unconventional Monetary Policy

What kind of capital goods were more likely to be invested by firms during the period under study? If firms were quite risk-averse or they followed the safety-first principle, then, according to the predictions of our theoretical model, they preferred the current or existing machines to the new machines. Of course, this does not imply that no firms would invest in new machines, as there were probably a small handful of entrepreneurs who were less risk-averse than the others, if not risk-neutral or risk-loving. Nor does it imply that risk-averse firms did not invest

in new machines during the years 2015-2019 when the market was quite stable. Nonetheless, the deferment of investment or the investment in the old machines during the years 2009-2015 could, on average, pull down the overall productivity of the jelly capital stock for the entire second subperiod 2009-2021, not to mention the decline in investment again in 2020 because of the coronavirus pandemic.

Our empirical findings above are based on data at the aggregate or sectoral level. While further empirical analysis based on micro-data at the firm level is left for future research, there is documentary evidence at the firm level in support of our hypothesis. In the US construction industry, for instance, new machine sales were usually 60-80% of used sales before the Great Recession; but used machine sales were more than double new machine sales in 2009 and more than three times higher in 2011 (Equipment World 2011). In the auto industry, General Motors halted construction of a brand-new engine plant of high-tech facility and next generation production machinery in Flint, Michigan in 2008 and retrofitted its aging Flint South engine plant instead. Chrysler and Ford also retrofitted their plants (NPR December 17, 2008). Cases in which corporations cancelled or postponed high-tech, high-productivity options and turned back to older, less efficient technologies in the printing, media, and telecom sectors between 2008 and 2010 were also reported.

IV. Discussion

4.1 Limitations and Policy Implications

Although our empirical results based on a vintage growth model indicate a decline in technical progress during the era of unconventional monetary policy and we build a micro-theoretical model of buffer stock money and investment together with SVAR estimation results to further support this finding, it should be emphasized that we should be careful in interpreting the findings and drawing the conclusions and policy recommendations, because of the assumptions and limitations of our analytical and empirical frameworks.

Limitations of this study are many and not difficult to find. We do not list them out and discuss them one by one here simply because of limited space. For example, the concept of capital and hence its measurement has long been a controversial issue in both the voluminous theoretical

and empirical literatures. Another example is that, for the purpose of this study, we have confined technical progress to be entirely embodied in capital goods; but in both theory and practice, technical progress can be embodied in labour or it can be disembodied as well. Yet another example is: our empirical findings are so aggregative that we cannot tell which industries were innovative and which ones lagged behind in investment unless we conduct empirical analysis based on data at the industry or firm level. And the list goes on. Admittedly, the above empirical and theoretical analyses contain many unresolved issues that need to be addressed in future research.

So instead of going into discussing in detail these limitations, we focus here on the question: What lessons and policy implications do we learn from our theoretical and empirical study?

First, lower interest rates do not necessarily induce more investment and hence promote technical progress and economic growth. There is asymmetry of interest-rate effect due to monetary policy -- higher interest rate reduces investment, but lower interest rate does not necessarily induce more investment. This asymmetry has long been recognized by earlier writers like Hawtrey (1938) and Hicks (1977), among others. There are announcement or psychological effects associated with a change in the policy rate by the central bank as the public would form expectations about the monetary authority's policy stance and future interest rate changes. When an increase in the policy rate is interpreted as a signal of contractionary monetary policy, the public will form expectations and cut their borrowings accordingly. Because of their expectations and actions, a contractionary monetary policy that originally would require an increase of interest rate by, say, 6% may now be possible with a smaller increase by, say, 4% only. By contrast, an expansionary monetary policy may require a larger cut in interest rate than the monetary authority originally intended when the public expect there would be further cuts in interest rates and hence hold back their borrowings and investment projects accordingly. This latter scenario offers another perspective to explain investment behaviour when QE was initially introduced. Similarly, our findings also indicate that the US Fed could not stimulate private investment even if interest rates were pushed to zero or even negative in real terms. As a matter of fact, this asymmetry in monetary policy was recognized four decades ago before QE by Milton Friedman (1968):

“Monetary policy was a string. You could pull on it to stop inflation but you could not push on it to halt recession.” Or simply put, one can take a horse to the water but one can’t make it drink!

Second, even if lower interest rates succeed in stimulating investment, firms do not necessarily invest in the best technology or techniques available. Our study demonstrates, more formally with theory and empirical evidence, that this can be the case. If the technical progress function can be shifted downward by lower interest rates due to expansionary or unconventional monetary policy, it may mean that the policy can hinder or delay the economy from reaching a higher long-run growth path. A central bank may implement QE as an unconventional policy to stabilize the economy after a major economic or financial crisis, as in the cases of the US Fed following the GFC and the Bank of Japan in the 1990s. But there is no free lunch. Our results suggest that the central banker should consider the intertemporal welfare trade-off between short-run stabilization and long-run economic growth in the formulation and implementation of its monetary policy.

Last but not least, there has been an extensive literature on whether monetary rules or the use of discretion by the monetary authority is more effective in stabilizing the economy (see Taylor 2018 for a recent assessment). We do not go into this debate here but instead we ask: what kind of monetary policy stance will be favourable to technical progress? Our theoretical model and the empirical evidence tend to suggest that a monetary rule is more favourable than discretionary monetary policy. On the surface, this rule-based policy implication may not be obvious. But if we reconsider the setup of our simple model, we should notice that changes in the interest rate together with the random q ’s will affect output Q_I (see Equation (7)). If the interest rate becomes more or less a random variable and less predictable by the public because of the central bank’s discretionary monetary policy stance, there will be larger output variations because, statistically speaking, the variance of Q is now the quotient of two random variables, i.e., q and r . It follows that a higher degree of risk or uncertainty would induce firms to defer their investment or to invest in the current machines rather than the new machines. This interpretation is, of course, based directly from our mathematical model. Admittedly, no sane central banker conducts monetary policy randomly. Nonetheless, a rule-based monetary policy would be preferable to discretion in reducing uncertainty and hence inducing investment.

4.2 Alternative Explanations

Our explanations and interpretations are by no means exclusive. The GFC, the Great Recession, and the Fed's QEs were impactful events reflecting respectively uncertainty, weak aggregate demand and expansionary monetary policy. The episode under study is such a complex economic phenomenon that our empirical framework and the use of macro-data do not identify a clean causal or policy effect. Nonetheless, we may view each of these events as an INUS condition or a "cause" in Mackie's (1980) conditional account of causality (see also Hoover 2001). Each event is *Insufficient* because no one condition alone could lead to our findings, and each is *Nonredundant*. Yet they are *Unnecessary Sufficient* because the outcome could have happened through other channels.

Admittedly, numerous studies have offered alternative mechanisms through which quantitative easing affects aggregate investment. The related literature is so voluminous that it is not the place here to give even a brief literature survey. It suffices for our purpose to highlight a couple of admissible theories or hypotheses and recent studies.

First, based on the experience of Japan's lost decades, for example, Koo (2009, 2015) argues that the Great Recession was a balance-sheet recession and the drastic interest-rate cuts due to QE had little stimulating effects on the economy because corporations prioritized revamp of their balance sheets ahead of business investment and expansion. More recently, Bacchetta et al. (2020) use a monetary model with asset scarcity to show that financial constraints and deleveraging can cause a persistent liquidity trap that increases real cash holdings and decreases investment and output in the medium term. In theory, financial frictions and deleveraging can engender the aggregate phenomena as observed following the outbreak of the GFC. Empirically, Boehl et al. (2024) estimate a macro-finance DSGE model on US data to show that QE eased financial conditions and facilitated a net increase in aggregate investment. More recently, Giambona et al. (2026) use micro-data to show that the Fed's QE increases firm-level investment for firms with bond market access. This corporate-bond lending channel is just another example of alternative mechanisms.

The list of possible transmission mechanisms can continue, but it is interesting to note that relatively fewer studies have examined the interaction between unconventional monetary policy

and productivity like this study does. Among these studies is Jorda et al. (2026), who show that monetary policy is not neutral and has real effects that last for a decade or more and that capital and total factor productivity growth are the main drivers of the long-lasting effects on output. To assess the impact of QE on productivity growth, Grimm et al. (2021) find a strong and heterogeneous response of corporate R&D investment under the ECB's Corporate Sector Purchase Program, where eligible companies increased significantly their investment in R&D, relative to similar ineligible companies operating in the same country and sector, because innovative companies with low debt levels were subsidized by the central bank. More recently, Albrizio et al. (2026) use a panel of Spanish firms from 2002 to 2019 to show that firms with higher marginal revenue product of capital responded more strongly to monetary easing, increasing both investment and debt and also that expansionary monetary policy improves capital allocation mainly through the intensive margin by relaxing financial constraints of productive but constrained firms.

On the other hand, from a Schumpeterian perspective of creative destruction, recessions have a cleansing effect of wiping out the fragile firms and help to boost average productivity growth as newly set up firms are more likely to use the latest technology and have high efficiency than the old firms. But QE that attempted to alleviate the severity of recessions on the one hand, also allowed those fragile, low-productivity zombie firms to survive, thus reducing productivity for the economy as a whole (e.g., Poloz 2022).

Our brief discussion above is by no means comprehensive. It should, however, reveal that various mechanisms can offer alternative explanations or interpretations to the same facts. They may appear to be observationally equivalent. For sure there are similarities, but there are also differences as well. These hypotheses and ours are, however, not necessarily mutually exclusive and may in fact be complementary. They are lenses for us to look at the different aspects of a complex economic phenomenon.

V. Conclusion

In this study, we have revisited an old, if not overlooked, debate in the literature on capital theory. According to Keynes, more roundabout production methods are not necessarily more efficient than

less capital-intensive methods, and that at zero interest rate the best methods of production would be some finite degree of capital intensity. To put differently, zero or negative interest rates would lead to investment in Rube Goldberg machines, at least in theory.

We empirically test the validity of this idea by adopting a vintage growth model and using the US data on capital productivity and capital deepening for the years 1985-2021, as the US unconventional monetary policy following the Great Recession serves as a “natural laboratory.” Our empirical findings indicate a structural change in 2009 shortly after the outbreak of the Great Recession, following which the technical progress function shifted downward even though the interest rate was close to the ZLB or even negative in real term. The rate of technical progress is found to have declined from 2.13% p.a. for the years 1985-2008 to a marginally lower rate of 2.08% p.a. for the subsequent years 2009-2021, even though the trend of capital deepening continued. This suggests that, on average, firms tended to invest in capital goods embodied with lower productivity or efficiency in the latter years.

We have also adopted an approach based on a simple theoretical model, narrative as well as vector autoregression results to support our findings by analysing firms’ investment behaviour under this regime of unconventional monetary policy. The high degree of uncertainty during this era caused firms or entrepreneurs to hold buffer-stock money rather than to invest so as to protect themselves from the adverse or unexpected consequences. However, this behaviour tended to hinder economic recovery and hence helped ensure the persistence of uncertainty. This interpretation is consistent with not only our econometric findings but also the fact that three rounds of QE programs were needed to revive the U.S. economy.

Our theory is by no means the unique explanation for the empirical findings. Strictly speaking, our study offers no compelling empirical evidence showing that zero or negative interest rate because of QE had induced firms to invest in Rube Goldberg machines, taken literally to mean inefficient and impractical, or even counterproductive, capital goods or equipment. After all, it would be both counterintuitive and counterfactual for firms to act irrationally to invest in such machines to harm their own productivity and profitability in both the short and long run. This perspective, however, will be too narrow-minded if profit maximization is regarded as firms’ sole objective without taking other factors, like risk aversion, into considerations.

But if the definition of Rube Goldberg machine is taken loosely to mean reproducible capital goods that do not belong to the latest vintage being the most efficient and productive, then both our theory and empirical evidence as well as certain reported cases in the media suggest that, under high degree of uncertainty and viewing negative interest rates as a subsidy, firms might have been induced to continue the capital deepening trend by investing in less efficient but safer capital goods rather than in the newest capital goods that are more efficient but also riskier. After all, a bird in hand is better than two in the bush. In this case, Keynes's argument in the *General Theory* is right – higher capital intensity does not imply higher capital productivity.

To conclude, we have explored and found some empirical evidence in support of Keynes's above idea about the relationship between capital intensity and production efficiency as he alluded to in his *General Theory*. Even though the empirical evidence may not be viewed as entirely compelling, it certainly rejects the opposing viewpoint held by some other economists that further capital deepening will always lead to higher capital productivity. Furthermore, Keynes might still be right; for the global trend of capital deepening today may not have yet reached the critical point, beyond which more capital-intensive production methods will raise the unit production costs. We leave this (re)search for Rube Goldberg machine to the future.

Data Appendix

The following is a list of the variable names, brief descriptions, data series numbers (if available) and sources of the data used in the empirical analysis of this paper. Most of the data were retrieved from the FRED Database of the Federal Reserve Bank of St. Louis. The sample period is 1985-2021.

Variable	Description	Series Number	Data Source
CD	Currency and transferable deposits held by nonfinancial corporate business, quarterly	FL103020005.Q	Financial Accounts of the United States, Board of Governors of the Federal Reserve System
Fed Fund Rate	Fed fund effective rate, annual average	RIFSPFFNA	Board of Governors of the Federal Reserve System, via FRED
GDP Deflator	Gross Domestic Product: Implicit Price Deflator, annual average	A191RI1Q225SBEA	U.S. Bureau of Economic Analysis, via FRED
KE	Equipment held by nonfinancial corporate business, quarterly	LM105015205.Q	Financial Accounts of the United States, Board of Governors of the Federal Reserve System
KLR	Capital Deepening Index, annual	n.a.	OECD Productivity Database
KPI	Capital Productivity Index, annual	n.a.	OECD Productivity Database
MB	Monetary Base, quarterly average	BOGMBASE	Board of Governors of the Federal Reserve System, via FRED
PNRI	Real private non-residential fixed investment, annual	PNFIC1	U.S. Bureau of Economic Analysis, via FRED
VIX	CBOE Volatility Index	VIXCLS	Chicago Board Options Exchange via FRED

References

- Abel, A.B., A.K. Dixit, J.C. Eberly, and R.S. Pindyck (1996) "Options, the Value of Capital, and Investment." *Quarterly Journal of Economics* 111: 753-77. [Options, the Value of Capital, and Investment* | The Quarterly Journal of Economics | Oxford Academic](#)
- Albrizio, S., B. Gonzales, and D. Khametshin (2026) "A Tale of Two Margins." *European Economic Review* 185: article 105278. <https://www.sciencedirect.com/science/article/pii/S001429212600022X#b24>.
- Bacchetta, P., K. Benhima, and Y. Kalantiz (2020) "Money and Capital in a Persistent Liquidity Trap." *Journal of Monetary Economics* 116: 70-87. [Money and Capital in a Persistent Liquidity Trap](#)
- Bateman, Bradley W. (1987) "Keynes's Changing Conception of Probability." *Economics and Philosophy* 3: 97-120. [Bradley W. Bateman, Keynes's Changing Conception of Probability - PhilPapers](#).
- Bernanke, B.S. (1983) "Irreversibility, Uncertainty, and Cyclical Investment." *Quarterly Journal of Economics* 98: 85-106. [Irreversibility, Uncertainty, and Cyclical Investment* | The Quarterly Journal of Economics | Oxford Academic](#)
- Bernanke, B.S. (2022) *21st Century Monetary Policy: The Federal Reserve from the Great Inflation to COVID-19*. New York: W.W. Norton & Co.
- Boehl G., G. Goy, and F. Strobel (2024) "A Structural Investigation of Quantitative Easing." *Review of Economics and Statistics* 106: 1028-44. [A-Structural-Investigation-of-Quantitative-Easing](#)
- Caballero, R.J. (1999) "Aggregate Investment" in J.B. Taylor and M. Woodford (eds.) *Handbook of Macroeconomics* Vol. 1B, Amsterdam: Elsevier: 813-62.
- Carr, J., and M. Darby (1981) "The Role of Money Supply Shocks in the Short-run Demand for Money." *Journal of Monetary Economics* 8: 182-200. [The role of money supply shocks in the short-run demand for money - ScienceDirect](#)
- Clower, Robert (1967) "A Reconstruction of the Microfoundations of Monetary Theory." *Western Economic Journal* 6: 545-56. [A RECONSIDERATION OF THE MICROFOUNDATIONS OF MONETARY THEORY - CLOWER - 1967 - Economic Inquiry - Wiley Online Library](#)
- Engle, R.E., and C.W.J. Granger (1987) "Cointegration and Error-Correction: Representation, Estimation and Testing." *Econometrica* 55: 251-76. [Co-Integration and Error Correction: Representation, Estimation, and Testing on JSTOR](#)

- Equipment World (March 4, 2011) “Special Report: Equipment’s Brave New World” <https://www.equipmentworld.com/roadbuilding/article/14948599/special-report-equipments-brave-new-world>.
- Ferguson C.E. (1969) *The Neoclassical Theory of Production and Distribution*. Cambridge: Cambridge University Press.
- Fraumeni, B.M. (1997) “The Measurement of Depreciation in the U.S. National Income and Product Accounts,” *Survey of Current Business* (July): 7-23.
- Friedman, M. (1956) “The Quantity Theory of Money: A Restatement,” pp. 3-21 in M. Friedman (ed.) *Studies in the Quantity Theory of Money*. Chicago: Chicago University Press.
- Friedman, M. (1968) “The Role of Monetary Policy.” *American Economic Review* 58: 1-17. [The Role of Monetary Policy](#)
- Friedman, M., and A.J. Schwartz (1963) *A Monetary History of the United States, 1867-1960*. Princeton: Princeton University Press.
- Garrison, R. (2002) *Time and Money: The Macroeconomics of Capital Structure*. London: Routledge.
- Giambona, E., R. Matta, J-L Peydro, and Y. Wang (2026) “Quantitative Easing, Investment, and Safe Assets: The Corporate Bond–Lending Channel.” *Journal of Money, Credit and Banking* 58: 329-64. <https://onlinelibrary.wiley.com/doi/10.1111/jmcb.13272>
- Goodhart, C.A.E. (1989) *Money, Information and Uncertainty*, 2nd edition, Cambridge: MIT Press.
- Gregory, A., and B. Hansen (1996) “Residual-based Tests for Cointegration in Models with Regime Shifts.” *Journal of Econometrics* 10:321-335. [Residual-based tests for cointegration in models with regime shifts - ScienceDirect](#)
- Grimm, N., L. Laeven, and A. Popov (2021) “Quantitative Easing and Corporate Innovation” Working Paper Series No. 2625, European Central Bank. <https://www.ecb.europa.eu/pub/pdf/scpwps/ecb.wp2615~c8d4f9a229.en.pdf>
- Hawtrey, R. (1938) *A Century of Bank Rate*. New York: Longman, Green and Co.
- Hayek, F.A. (1941) *The Pure Theory of Capital*. London: Routledge & Kegan Paul.
- Hicks, J.R. (1935) “A Suggestion for Simplifying the Theory of Money.” *Economica* 2: 1-19. [A suggestion for simplifying the theory of money](#).
- Hicks, J.R. (1937) “Mr. Keynes and the Classics: A Suggested Interpretation.” *Econometrica* 5: 147-59.
- Hicks, J.R. (1965) *Capital and Growth*. Oxford University Press.

- Hicks, J.R. (1967) “The Two Triads,” pp. 1-60 in his *Critical Essays in Monetary Theory*. Oxford: Clarendon Press.
- Hicks, J.R. (1973) *Capital and Time: A Neo-Austrian Theory*. Oxford University Press.
- Hicks, J.R. (1974a) “Capital Controversies: Ancient and Modern.” *American Economic Review* 64: 307-16. [Capital Controversies: Ancient and Modern on JSTOR](#)
- Hicks, J.R. (1974b) *The Crisis in Keynesian Economics*. Oxford: Basil Blackwood.
- Hicks, J.R. (1977) “Hawtrey,” pp. 118-33, in his *Economic Perspectives: Further Essays on Money and Growth*. Oxford: Clarendon Press.
- Hicks, J.R. (1979) *Causality in Economics*. Oxford: Basil Blackwood.
- Hicks, J.R. (1985) *Methods of Dynamic Economics*. Oxford: Clarendon Press.
- Hoover, K. (2001) *Causality in Macroeconomics*. Cambridge: Cambridge University Press.
- Jorda, O., S.R. Singh, and A.M. Taylor (2026) “The Long-Run Effects of Monetary Policy.” *Review of Economics and Statistics* 108: 1-21. [The-Long-Run-Effects-of-Monetary-Policy](#).
- Jorgenson, D.W., and F. Griliches (1967) “The Explanation of Productivity Change.” *Review of Economic Studies* 34: 249-83. [EconPapers: The Explanation of Productivity Change](#)
- Jones, R. and J.M. Ostroy (1984) “Flexibility and Uncertainty.” *Review of Economic Studies* 51: 13-32. [Flexibility and Uncertainty | The Review of Economic Studies | Oxford Academic](#)
- Kaldor, N. (1957) “A Model of Economic Growth.” *Economic Journal* 67: 591-624. [Model of Economic Growth | The Economic Journal | Oxford Academic](#)
- Keynes, J.M. (1921 [1973]) *A Treatise on Probability, Collected Writings, VIII*. London: Macmillan.
- Keynes, J.M. (1923) *A Tract on Monetary Reform*. New York: Prometheus Books.
- Keynes, J.M. (1930) *A Treatise on Money Volume I: The Pure Theory of Money*, London: Macmillan & Co.
- Keynes, J.M. (1936) *The General Theory of Employment, Interest and Money*. Macmillan Cambridge University Press.
- Keynes, J.M. (1937a) “The General Theory of Employment.” *Quarterly Journal of Economics* 51: 209-23. [General Theory of Employment | The Quarterly Journal of Economics | Oxford Academic](#)

- Keynes, J.M. (1937b) “Alternative Theories of the Rate of Interest” *Economic Journal* 47: 241-52. <https://hetwebsite.net/het/texts/keynes/keynes1937alternative.pdf>.
- Knight, F. (1921 [1971]) *Risk, Uncertainty and Profit*. Chicago: University of Chicago Press.
- Koo, Richard (2009) *The Holy Grail of Macroeconomics: Lesson from Japan’s Great Recession*. N.J.: John Wiley & Sons.
- Koo, Richard (2015) *The Escape from Balance Sheet Recession and the QE Trap: A Hazardous Road for the World Economy*. Singapore: Wiley.
- Laidler, D.E.W. (1984) “The Buffer Stock Notion in Monetary Economics.” Supplement to *Economic Journal* 94: 17-33. [‘Buffer Stock Notion in Monetary Economics | The Economic Journal | Oxford Academic](#)
- Laidler, D.E.W. (1987) “Buffer-Stock Money and the Transmission Mechanism.” *Economic Review*, Federal Reserve Bank of Atlanta (March): 11-23. [Economic Review \(Federal Reserve Bank of Atlanta\), March/April 1987, Volume 72, Number 2 | FRASER | St. Louis Fed](#)
- Laidler, D.E.W. (1990) *Taking Money Seriously and Other Essays*. Cambridge: MIT Press.
- Laidler, D.E.W. (1999) *Fabricating the Keynesian Revolution: Studies of the Inter-war Literature on Money and Cycle. and Unemployment*. Cambridge University Press.
- Leijonhufvud, Axel (1968) *On Keynesian Economics and the Economics of Keynes*. New York: Oxford University Press.
- Mackie, J.L. (1980) *The Cement of the Universe: A Study in Causation*, 2nd ed. Oxford: Clarendon Press.
- Makowski, L. (1989) “Keynes’s Liquidity Preference Theory: A Suggested Reinterpretation,” pp. 468-75 in F. Hahn (ed.) *The Economics of Missing Markets, Information and Games*. Oxford: Clarendon Press.
- Milbourne, R. (1988) “Disequilibrium Buffer Stock Models: A Survey.” *Journal of Economic Surveys* 2: 187-208. [DISEQUILIBRIUM BUFFER STOCK MODELS: A SURVEY - Milbourne - 1988 - Journal of Economic Surveys - Wiley Online Library](#)
- Miller, M.H., and D. Orr (1966) “A Model of the Demand for Money by Firms.” *Quarterly Journal of Economics* 80: 413-35. [Model of the Demand for Money by Firms* | The Quarterly Journal of Economics | Oxford Academic](#)
- Nelson, R.R. (1964) “Aggregate Production Function and Medium Range Growth Projections.” *American Economic Review* 54: 575-606. [Aggregate Production Functions and Medium-Range Growth Projections on JSTOR](#)

- NPR (December 17, 2008) “Chrysler, Ford Idle Factories; GM Delays New Plant.” <https://www.npr.org/2008/12/17/98420426/chrysler-ford-idle-factories-gm-delays-new-plant>.
- OECD (2009) *Measuring Capital OECD Manual*, 2nd edition. Paris: OECD.
- OECD (2021) *OECD Productivity Statistics Database Methodological Notes*. Paris: OECD.
- Orr, D. (1970) *Cash Management and the Demand for Money*. New York: Praeger.
- Park, J.Y. (1992) “Canonical Cointegration Regressions.” *Econometrica* 60: 119-43. [Canonical Cointegrating Regressions on JSTOR](#)
- Perron, P. (1989) “The Great Crash, the Oil Price Shock, and the Unit Root Hypothesis.” *Econometrica* 57: 1361-1041. [The Great Crash, the Oil Price Shock, and the Unit Root Hypothesis | The Econometric Society](#)
- Phelps, E. (1962) “The New View of Investment: A Neoclassical Analysis.” *Quarterly Journal of Economics* 76: 548-67. [New View of Investment: A Neoclassical Analysis* | The Quarterly Journal of Economics | Oxford Academic](#)
- Poloz, Stephen (2022) *The Next Age of Uncertainty: How the World Adapt to a Riskier Future*. Penguin Random House Canada.
- Roy, A.D. (1952) “Safety First and the Holding of Assets.” *Econometrica* 20: 431-49. [Safety First and the Holding of Assets on JSTOR](#)
- Schreyer, P. (2004) “Capital Stocks, Capital Services and Multi-factor Productivity Measures.” *OECD Economic Studies* 37: 163-84. [EconPapers: Capital Stocks, Capital Services and Multi-Factor Productivity Measures](#)
- Solow, R.M. (1960) “Investment and Technical Progress,” in K.J. Arrow et. Al. (eds.) *Mathematical Methods in Social Sciences*. Stanford, California: Stanford University Press: 89-104.
- Solow, R.M. (1962) “Technical Progress, Capital Formation, and Economic Growth.” *American Economic Review Papers and Proceedings* 52: 76-86. [Technical Progress, Capital Formation, and Economic Growth on JSTOR](#)
- Solow, R.M. (2008) “‘Distribution and Economic Progress’ after 70 years,” pp. 277-86 in R. Scazzieri, A. Sen, and S. Zamagni (eds.) *Markets, Money and Capital: Hicksian Economics for the Twenty-first Century*. Cambridge: Cambridge University Press.
- Taylor, John B. (2018) “Rules versus Discretion: Assessing the Debate over the Conduct of Monetary Policy.” SIEPR Working Paper No. 17-045. Standford: Institute for Economic

Policy Research. [Rules-versus-discretion-assessing-debate-over-conduct-monetary-policy](#).

- Tsiang, S.C. (1966) “Walras’ Law, Say’s Law, and Liquidity Preference in General Equilibrium.” *International Economic Review* 7: 329-45. [Walras' Law, Say's Law and Liquidity Preference in General Equilibrium Analysis on JSTOR](#)
- Uzawa, H. (1961) “Neutral Inventions and the Stability of Growth Equilibrium.” *Review of Economic Studies* 28: 117-24. [Neutral Inventions and the Stability of Growth Equilibrium on JSTOR](#)
- Vines, David, and Samuel Wills (2018) “The Rebuilding Macroeconomic Theory Project: An Analytical Assessment.” *Oxford Review of Economic Policy* 34: 1-42. [The rebuilding macroeconomic theory project: an analytical assessment an analytical assessment on JSTOR](#)
- Vines, David, and Samuel Wills (2020) “The Rebuilding Macroeconomic Theory Project Part II: Multiple Equilibria, Toy Models, and Policy Models in a New Macroeconomic Paradigm.” *Oxford Review of Economic Policy* 36: 427-97. <https://samuelwills.net/wp-content/uploads/2021/01/vineswills2020.pdf>.
- Zivot, E. and D.W.K. Andrews (1992) “Further Evidence on the Great Crash, the Oil Price Shock, and the Unit Root Hypothesis.” *Journal of Business and Economic Statistics* 10: 251-70. [Further Evidence on the Great Crash, the Oil-Price Shock, and the Unit-Root Hypothesis on JSTOR](#)

Table 1: Results of Unit-Root Tests

	<i>KPI</i>		<i>KLR</i>	
	Level	First-difference	Level	First-difference
ADF Test				
Trend and Intercept	-1.735	-4.995***	-0.906	-4.0376**
Intercept	-0.6655	-5.092***	-0.8704	-4.062***
None	-4.6683***	-3.581***	7.6554	-2.360**
ADF Test with Breakpoint at 2008				
Trend & intercept break	-3.395	-7.045***	-2.970	-6.140***
trend break	-1.959	-5.315***	-2.156	-4.468**
Intercept break	-1.758	-5.241***	-0.666	-4.307***
No trend, intercept break	-0.237	-5.314***	0.523	-4.282**

Note:

1. *** denotes statistical significance at the one-percent level.
2. ** denotes statistical significance at the five-percent level.

Table 2: Results of Cointegration Tests

	Sample: 1985-2021	
Engle-Granger Test	τ -statistic	z-statistic
<i>KPI</i>	-2.562	-11.221
<i>KLR</i>	-2.560	-11.167
Johansen Test (no. of CE)	None	At most one
Trace statistics	23.01**	2.86
Max. Eigenvalue	20.151**	2.864
Gregory-Hansen Test	ADF statistic	Breakpoint (Year)
Level shift	-5.434***	2007
Level shift with trend	-5.333***	2007
Regime shift	-4.780***	2008
	Sample: 1985-2008	
Engle-Granger Test	τ -statistic	z-statistic
<i>KPI</i>	-4.032**	97.60
<i>KLR</i>	-3.876**	133.37
Johansen Test (no. of CE)	None	At most one
Trace statistics	21.065**	4.749
Max. Eigenvalue	16.315**	4.749
	Sample: 2009-2021	
Engle-Granger Test	τ -statistic	z-statistic
<i>KPI</i>	-5.643***	-18.079***
<i>KLR</i>	-5.430***	-17.987***
Johansen Test (no. of CE)	None	At most one
Trace statistics	25.815***	2.623
Max. Eigenvalue	23.191***	2.623

Note:

1. *** denotes statistical significance at the one-percent level.
2. ** denotes statistical significance at the five-percent level.

Table 3: Results of Cointegration Regressions

Dependent Variable	Estimation Method	
<i>KPI</i>	Engle-Granger	Canonical
Sample: 1985-2021		
Intercept	6.7584	6.7602
	(284.00)***	(177.41)***
<i>KLR</i>	-0.4662	-0.4670
	(-83.71)***	(-51.87)***
Adjusted R ²	0.9950	0.9944
CRDW	0.612	
Sample: 1985-2008		
Intercept	6.6120	6.6026
	(213.24)***	(160.83)***
<i>KLR</i>	-0.4294	-0.4270
	(-56.40)***	(-41.90)***
Adjusted R ²	0.9923	0.9920
CRDW	1.031	
Sample: 2009-2021		
Intercept	6.6494	6.6000
	(50.33)***	(90.19)***
<i>KLR</i>	-0.4439	-0.4331
	(-15.52)***	(-27.16)***
Adjusted R ²	0.9523	0.9514
CRDW	2.538	

Note: 1. Figures in parentheses are t-statistics.
2. *** denotes statistical significance at the one-percent level.
3. For brevity, results of the Engle-Granger error correction model are not reported here.

Table 4: Regression Results of Structural Change between Capital Productivity and Capital Intensity

	Coefficient estimate	OLS t-statistic	White's t-statistic
Intercept_1985-2008	0.006876	1.79*	2.21**
Slope_1985-2008	-0.6773	-6.06***	-7.16***
Intercept_2009-2021	0.005662	2.59**	2.45**
Slope_2009-2021	-0.7276	-11.15***	-17.76***
Adjusted R ²	0.7992		
S.E. of Regression	0.007176		
F-statistics	47.43***		
Durbin-Watson	2.0392		
Breusch-Pagan-Godfrey Heteroscedasticity Test	0.4716		
Jarque-Bera Normality Test	1.8376		

Note: ***, ** and * denote respectively statistical significance at the one-percent, five-percent level and ten-percent levels.

Table 5: Implied Technical Progress Functions from Regression Results

Years	1985-2008	2009-2021
Intercept	0.006876	0.005662
Slope (α)	0.3227	0.2724
Implied rate of technical progress (λ_k)	0.02131	0.02079

-

Figure 1: Investment and Capital Productivity
United States, 1985-2021

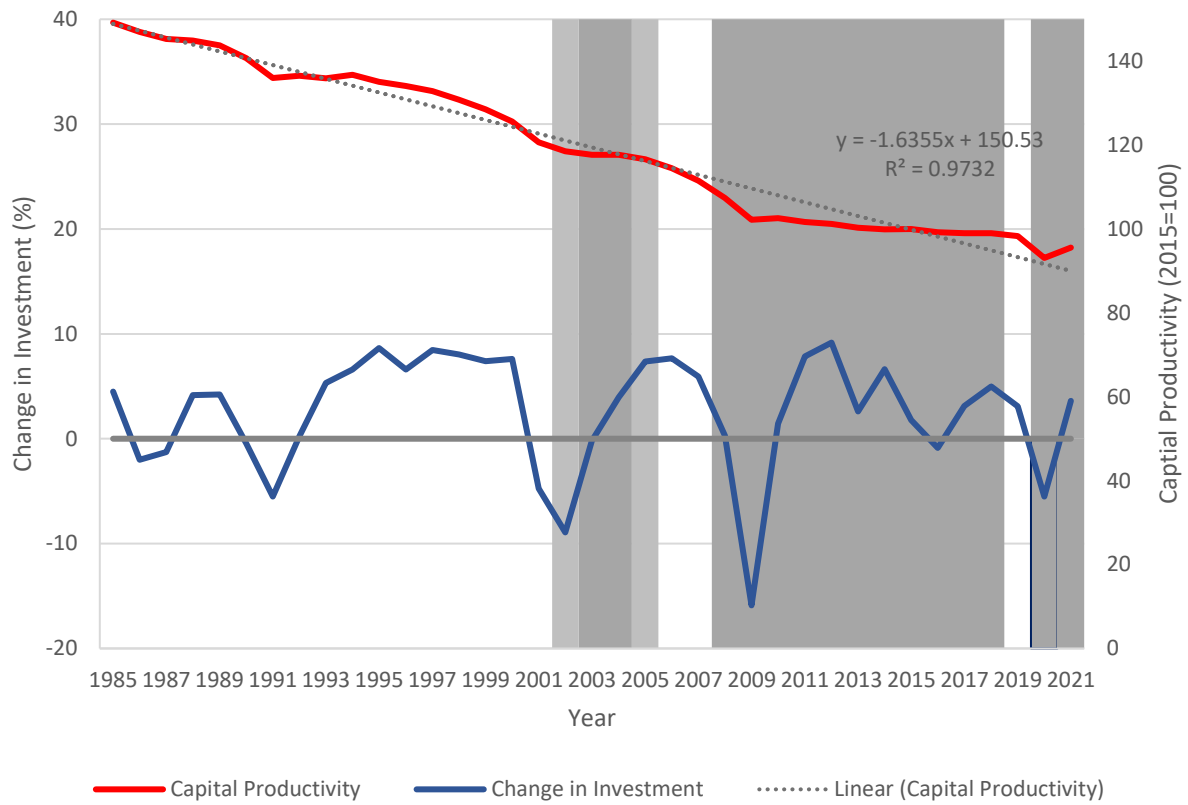


Figure 2: Effects of Money & Uncertainty on Investment

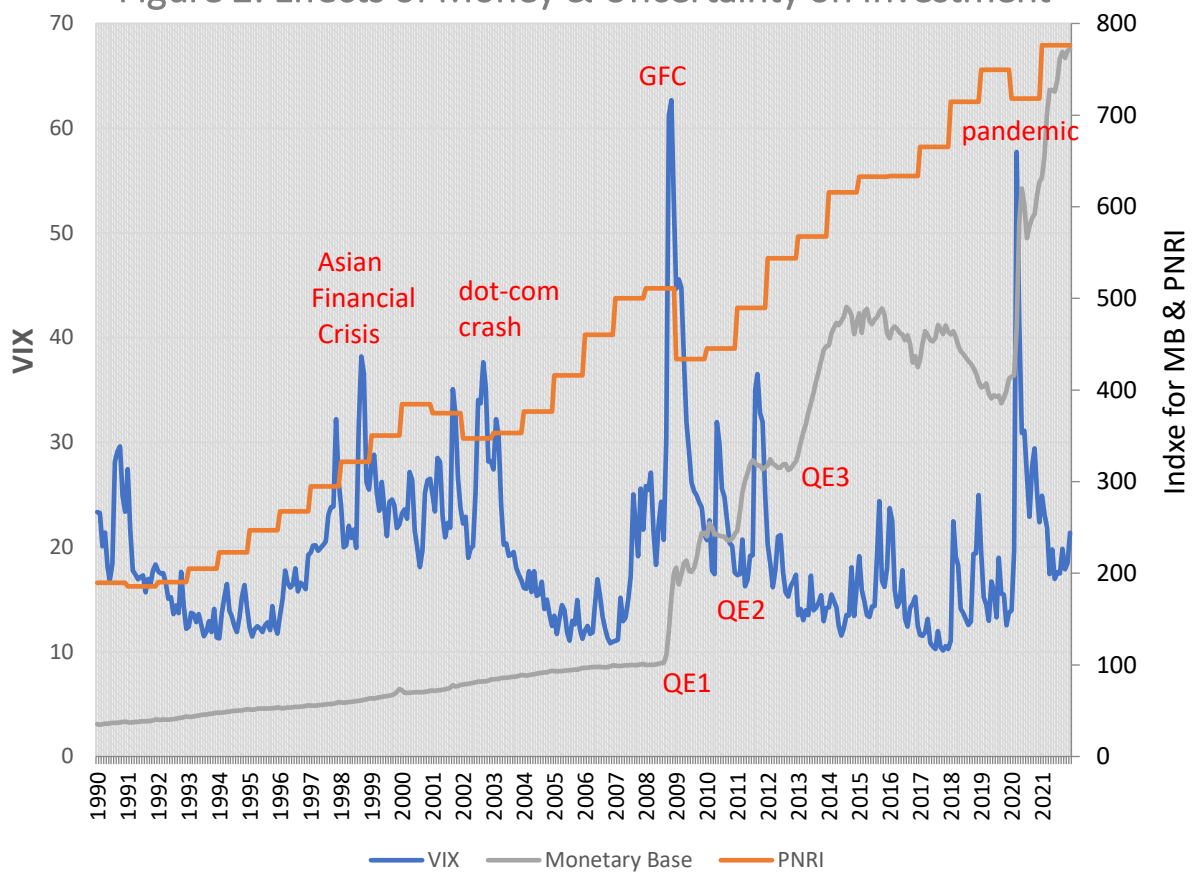


Table 6: Vector Autoregression Results

2007.Q3 – 2021.Q4, N = 58

Equation	Equipment ($\dot{KE}_t$)		Money ($\dot{CD}_t$)	
SVARX Results				
Structural coefficient	$\alpha_1 = 0.011$	$(1.75)^*$ [1.75] [*]	$\beta_1 = 4.591$	$(1.75)^*$ [1.75] [*]
Identification restriction	$\beta_1 = 0$		$\alpha_1 = 0$	
VARX Results				
$\dot{KE}_{t-1}$	0.441	$(3.89)^{***}$ [3.72] ^{***}	-3.693	$(-1.59)^*$ [-1.52] [†]
$\dot{CD}_{t-1}$	-0.0108	$(1.68)^*$ [-1.60] [†]	0.0379	(0.29) [0.27]
$\dot{MB}_t$	0.0143	$(2.18)^{**}$ [2.08] ^{**}	-0.260	$(-1.93)^{**}$ [-1.85] [*]
VIX_{t-1}	-0.0307	$(-3.76)^{***}$ [-3.59] ^{***}	0.221	$(1.32)^{\dagger}$ [1.26]
Constant	1.082	$(5.21)^{***}$ [4.98] ^{***}	3.498	(0.82) [0.79]
R ²	0.4244		0.1298	
χ^2	20.13 ^{***}		8.53 [*]	
F-stat.	9.77 ^{***}		1.98 [†]	
Jarque-Bera normality test	13.52 ^{***}		1.87	
LR test for lag order selection	21.99 ^{***}	2.86	5.83	4.53
	one lag	two lags	three lags	four lags
LM test for residual autocorrelation	1 st order: 0.69	2 nd order: 4.02	3 rd order: 0.65	4 th order: 7.87 [*]
Eigenvalue stability condition		0.5233	-0.0442	

Note:

- Figures in parenthesis are t statistics; those with small sample degree-of-freedom adjustments are in brackets.
- P-values are denoted by [†], ^{*}, ^{**} and ^{***} respectively for $p < 0.01$, $p < 0.2$, $p < 0.1$, $p < 0.05$, and $p < 0.01$.

Figure 3: Impulse Response Functions

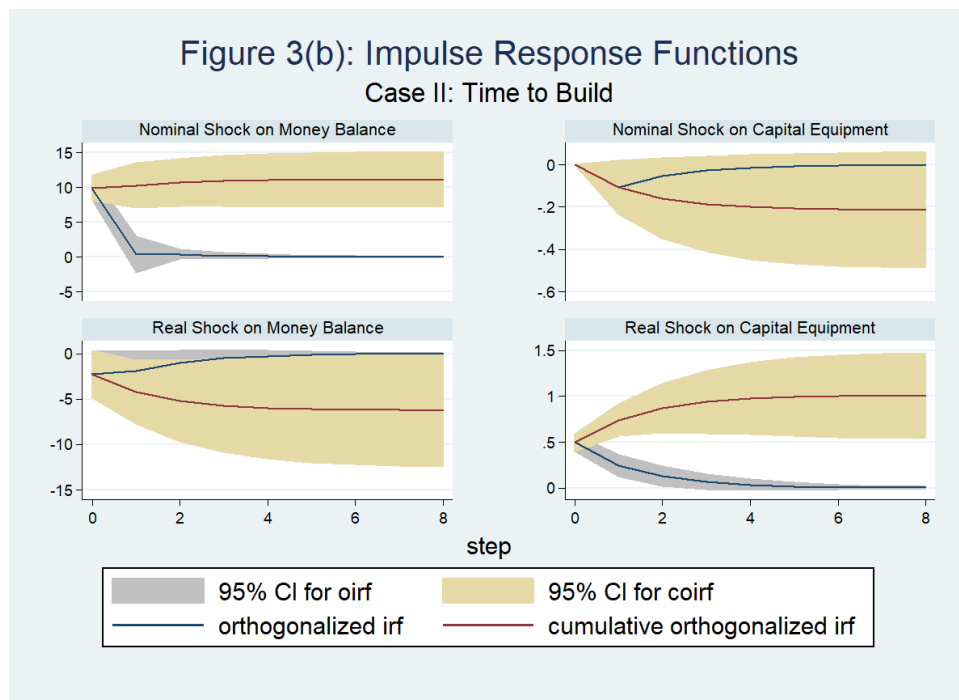
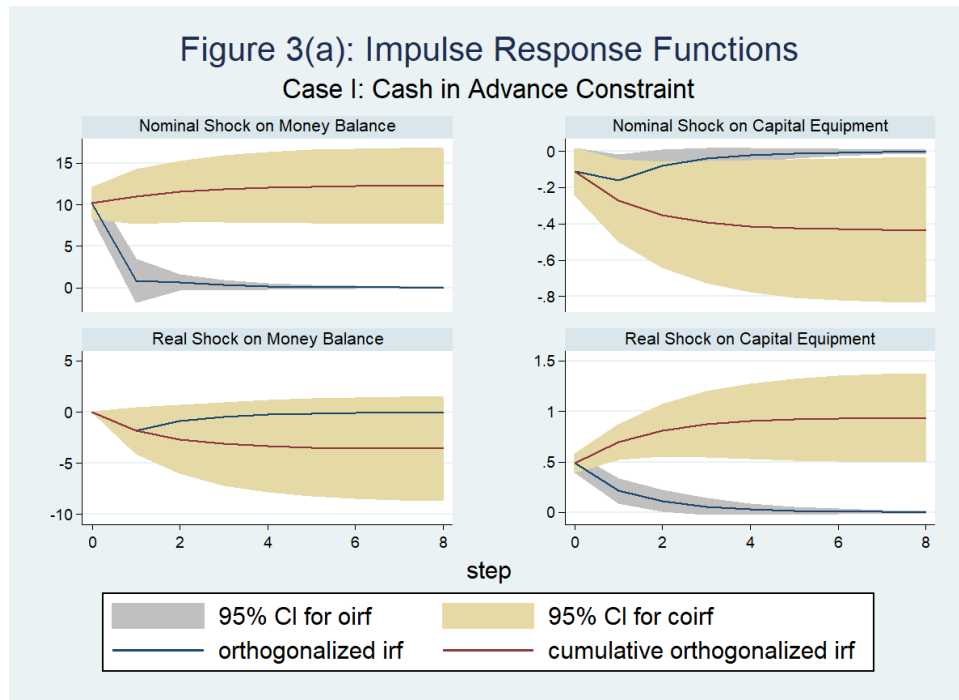


Figure 4: Dynamic Multiplier Functions
Impacts of Uncertainty and Quantitative Easing

