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## OBSOLESCENCE


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# ABSTRACT

## Obsolescence*

Does it always pay to install high-quality capital? Or could it possibly be more profitable to make investments that do not last too long? In this Paper we ponder the optimal rate of depreciation of physical capital, first in the Solow model and then in a model of endogenous growth with learning by doing. Optimal durability and depreciation, including obsolescence, are attained when the marginal benefit of increasing durability – and thus reducing the need for future replacement investment – is equal to the marginal cost, which is the additional cost of investing due to the higher quality of capital. The optimality conditions are set out as golden rules for the quality, or durability, of capital. They entail that the higher the rate of population growth or technological progress, the larger the marginal cost of investing in durability and the lower the optimal level of durability; hence, the higher the optimal rate of depreciation. We then use a customer market model to derive the privately optimal level of durability, and find that there is nothing in the model that ensures the socially optimal level of durability and depreciation.

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# NON-TECHNICAL SUMMARY

Around the world, differences in the quality of housing, capital and infrastructure are at least as evident as differences in the quantity of such capital. Comparing cities, we see vast differences in the quality of housing and other infrastructure. How can differences in the quality of capital across countries be explained and how they are related to economic growth?

Quality, as we define it, is closely related to depreciation – due to economic obsolescence or physical wear and tear. Physical depreciation is a technological phenomenon. A tractor wears out with normal use, and ultimately breaks down. By economic depreciation we mean obsolescence. Even if it may be technologically feasible to keep a tractor in running order for decades on end, it ceases to make economic sense at some point because the upkeep ultimately becomes too expensive compared with the cost of a new and better tractor. In growth theory, depreciation has traditionally been taken to be almost a constant of nature that affects the steady-state level of both capital and output per head and medium-term growth in the Solow model, and the long-run rate of growth of output *per capita* in endogenous growth models. It has not, however, been presented as one of the movers or shakers of economic growth.

Producers of capital equipment have, however, considerable leeway in deciding the durability of the equipment. We look at this optimization problem from a macroeconomic standpoint by deriving the optimal level of quality – that is, the one that either maximizes consumption in steady state or the rate of growth of output – and relating this to factors such as saving and investment rates and economic growth. We also ask whether private firms are likely to choose the level of quality of capital that is optimal from a macroeconomic or social standpoint.

We think of quality in two dimensions, *productivity* and *durability*. While we take productivity to be an exogenous variable for most of our analysis, durability is endogenous throughout. When investing, firms decide on the level of spending needed to ensure durability of the new capital equipment: by spending more at the time of investment, they can make the capital last longer. Thus, by spending more on a given investment, firms need to spend less replacing worn-out or obsolete capital later on.

On one hand, quality reflects the average productivity of capital. A low-productivity unit of capital is only partially usable in production because it has been allocated to inefficient uses or because it is old, whereas a high-quality unit is completely usable. Some machines can only be used a few hours each day due to costly and time-consuming maintenance procedures (e.g. the

Concorde). Another example is capital that is virtually useless, such as the concrete bunkers scattered all across Albania under Enver Hoxha's leadership. Even so, these bunkers are of high quality in the sense of being almost indestructible. On the other hand, quality mirrors the durability of capital. A low-quality unit of capital is one that is not going to last very long while the highest quality brings maximum durability. In this case, Mr Hoxha's bunkers come out near the top of the list, for despite low productivity they have indeed proved almost indestructible. Modern computers, by contrast, can be very productive, but they are not very durable due to their rapid obsolescence. Productivity and durability thus do not always go hand in hand.

In growth theory thus far, as we have said, depreciation and obsolescence have been regarded as exogenous phenomena through some form of exponential decay. In the Solow model, more rapid depreciation reduces output and capital per head in the long run and hence the rate of growth of output per head in the medium term. In first-generation endogenous growth models, as in the Harrod-Domar model, increased depreciation reduces the rate of growth in output per head even in the long run. Our main aim here is to see what happens to the relationship between depreciation and growth if the rate at which machinery and equipment wears out or is rendered obsolete is a matter of managerial choice. For firms do have a choice: they can either keep the current cost of investment down by skimping on quality and accepting more rapid depreciation or obsolescence as a result, or they can choose to incur a higher initial cost of investment in order to build durable capital that depreciates slowly. We describe the representative firm's decision problem as involving a simultaneous but separable choice of the quantity and quality of capital in production, where by quality we mean durability, which, in turn, we take to be inversely related to depreciation.

This view of endogenous depreciation, including obsolescence, leads to some new results. (i) Increased population growth accelerates depreciation given our assumption of diminishing returns to durability because providing a rapidly growing population with high-quality capital is costly in terms of consumption foregone. Hence, economic growth slows in the medium term more than it would if depreciation were exogenous. This result means that the population drag on medium-term growth is stronger in our model than in the Solow model. In the long run, the adverse effect of population growth on the level of output per head is reinforced. (ii) Increased technological progress also accelerates depreciation for an analogous reason given our assumption of diminishing returns to durability, and thereby stimulates medium-term growth less than it would if depreciation were exogenous. This means that more rapid technological advance increases the level of output *per capita* less than it would if depreciation were exogenous, even if long-run *per capita* growth remains unchanged and equal to the rate of technological progress. (iii) Increased saving accelerates depreciation in our endogenous growth model given, once more, our assumption of diminishing returns to durability, thereby strengthening the positive effects of increased saving and investment on economic growth. This is because growth is the assumed maximand in this model, and higher saving and investment raise the cost of maintaining high quality: increased saving speeds up depreciation because that way growth also speeds up. (iv) Increased efficiency by whatever means – liberalization, privatization, stabilization, diversification, you name it – also increases depreciation in our endogenous growth model given, once again, our assumption of diminishing returns to durability, thereby strengthening the positive effects of increased efficiency on economic growth, for the same reasons as (iii) above.

The notion of dynamic efficiency in terms of the accumulation of capital is well established in the literature on economic growth. Models with overlapping generations and finite horizons demonstrate that there is no guarantee that a market economy will generate the optimal capital stock. When the working population cares about consumption in retirement or expects a decline in labour income, excessive saving can result. Our analysis extends this literature by deriving conditions – golden rules, if you prefer – for the optimal durability or quality of the capital stock. We show that this depends on population growth and technological progress – as does the optimal stock of capital in the standard formulation of dynamic efficiency – and also on the saving rate in a model of endogenous growth. We thus extend the notion of dynamic efficiency to cover the quality of capital. Moreover, we show that there is no guarantee that a market economy will generate the socially optimal quality of capital. Profit-maximizing producers of capital equipment may prefer low-quality output because such planned obsolescence will bring customers back for replacement purchases and reduce production costs. Concern about customer satisfaction and future market share is, however, a countervailing force.

The board room of the *Amalgamated Widget Company* Inc:

"Fifteen years ago we had a product whose quality was so bad that no one in his right mind would buy one of our widgets. Then, with improved engineering, production and quality control, we developed a reputation for having the best widgets on the market. Naturally our sales increased. Now our major problem is that our widgets are too good. They rarely break or wear out. As a consequence, most of the people who might want to buy a widget already have one. We tried changing the color and shape, but a person only needs one widget. We even tried TV commercials, but nothing worked. The only people who buy our product are people who don't already have one."

"Well," said the CEO, "what can we do to reverse this deplorable trend?"

The head of engineering speaks up: "We could … make a product that breaks down."

"If we do that," the head of sales said, "no one will buy our widgets the way they didn't buy them when we had a lousy product. They'd buy our competitor's widgets."

The CEO asked, "Couldn't we make it so that it was good enough to satisfy a customer, but broke down after a suitable period of time?"

"You mean like a few months after the guarantee expired?" said a young man who had just been promoted to the job of vice president for planning.

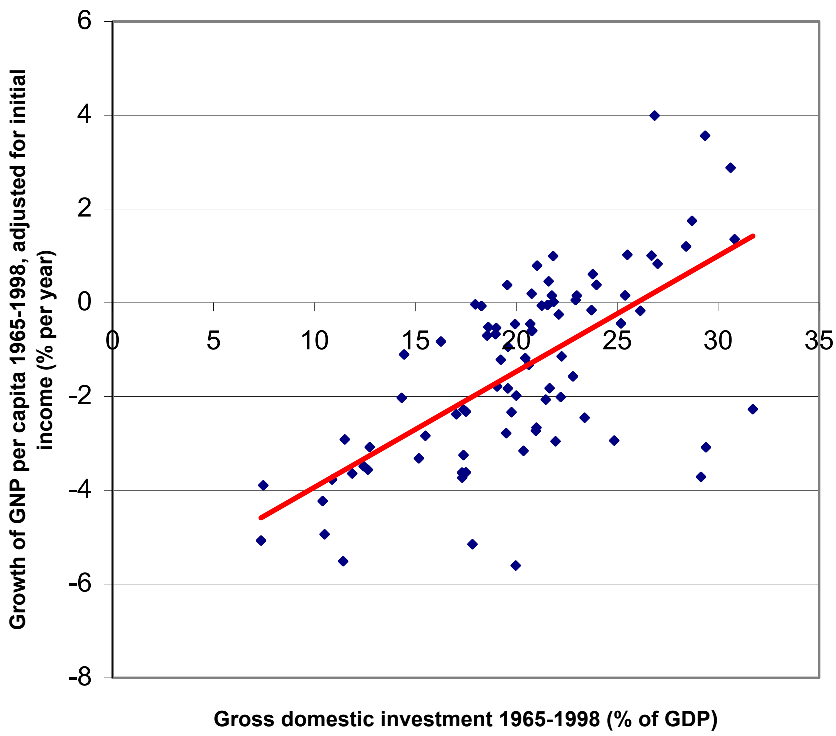
"We could do that simply by buying some inferior electronics parts, but we will have to be careful that they aren't too crummy," said the chief engineer.

Ira Pilgrim, *Mendocino County Observer*, September 2000.

The burgeoning empirical literature on economic growth suggests that differences in growth performance across countries since the 1960s – even countries that appear to have enjoyed similar fortunes as far as initial conditions, climate, culture and natural resources are concerned – can in some measure be traced to differences in gross saving and investment and hence in the quantity of accumulated capital. Thus, perhaps, it is hardly surprising that economic growth in Southeast Asia where saving and investment rates of 30 percent of gross domestic product are common has outpaced growth in Africa where, at least until recently, saving and investment rates of around 10 percent were the norm. Figure 1 shows a scatterplot of the average rate of growth of gross national product per capita and the average ratio of gross domestic investment to gross domestic product in 1965-1998. We have purged the growth variable of that part which is explained by the country's initial income per head by first regressing growth on the logarithm of initial income as well as on the share of natural capital in national wealth and then subtracting the initial income component from the observed growth rate. The regression line through the 85 observations in Figure 1 suggests that an increase in the investment ratio by four percentage points is associated with an increase in annual economic growth by about 1 percentage point.

The relationship is statistically as well as economically significant (Spearman's rank correlation $r = 0.65$, with $t = 7.8$). The slope of the regression line through the scatterplot is consistent with the coefficients on investment in cross-country growth regressions reported in recent studies (e.g., Levine and Renelt, 1992, and Barro and Sala-i-Martin, 1995).[1] The pattern observed is also broadly consistent with the experience of Southeast Asia and Africa: with saving and investment rates that have been roughly 20 percentage points higher than in Africa on average since 1965, Southeast Asia has experienced per capita growth that exceeds that of Africa by roughly 5 percentage points per year. It thus appears that, as far as the relationship between saving, investment and economic growth is concerned, quantity counts because, following standard practice, we measure investment by the volume of gross domestic investment. This practice means that net investment and replacement investment are assumed to have identical effects on economic growth.

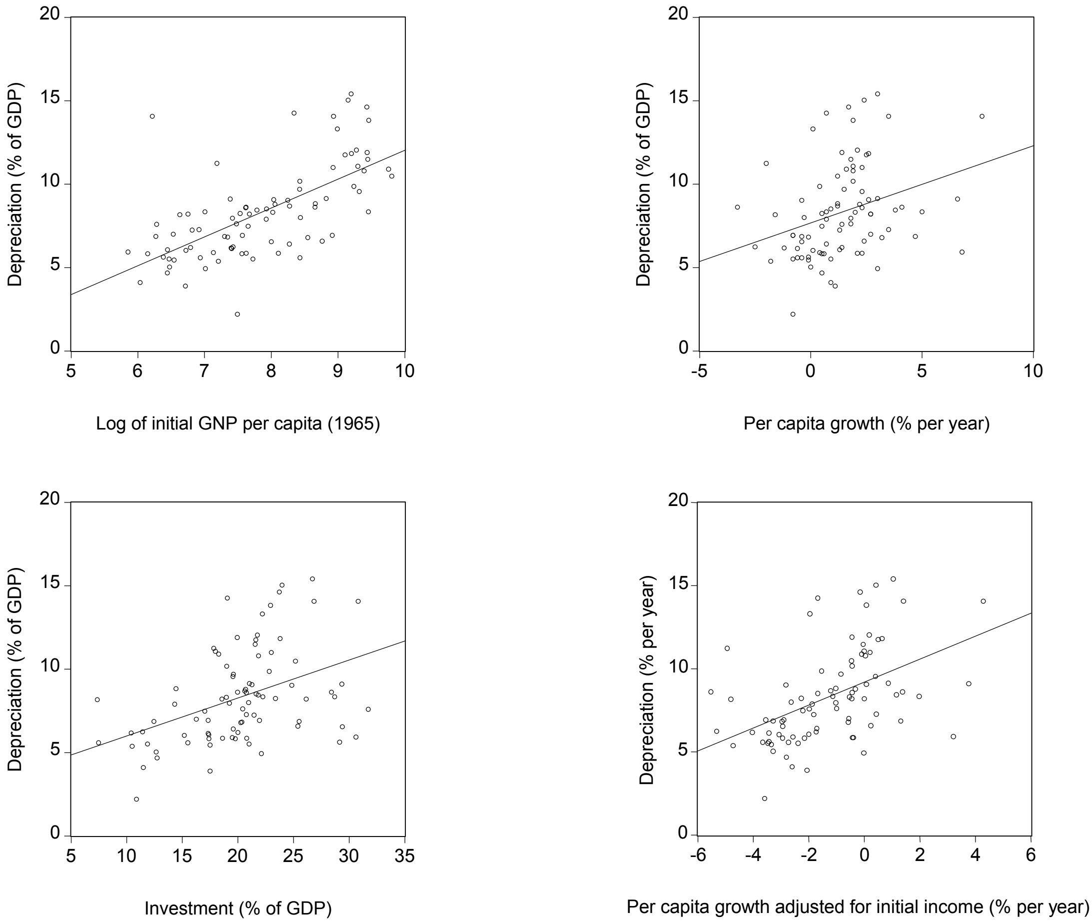
**Figure 1.** Economic Growth and Investment, 1965-1998




[1] Doppelhofer, Miller and Sala-i-Martin (2000) do not include investment among the 32 explanatory variables they consider in their study of the relative importance of the various potential determinants of long-run growth, presumably because they view investment, like growth, as an endogenous variable.

Around the world, differences in the quality of housing, capital and infrastructure are at least as evident as are differences in the quantity of such capital. Comparing the cities of the United States and Mexico, West and East Germany, Austria and Poland, Argentina and Paraguay, Thailand and Laos, and so on, we see vast differences in the quality of housing and other infrastructure. Whether of their own deserts or not, some nations are clearly more fortunate than others in being endowed with high-quality physical capital – and also human capital – even if their national income accounts often do not show these important differences. The question that we want to consider here is this: how can differences in the quality of capital across countries be explained and how they are related to economic growth?

**Figure 2.** Depreciation, Initial Output, Investment and Economic Growth, 1965-1998




Note: The scatterplots include 85 countries, the maximum number of countries for which all the variables listed in Table 1 are available from the World Bank (2000).

Data recently published by the World Bank (2000) show that average depreciation of fixed capital over the period 1970-1998[2] – measured as a proportion of GDP – is directly related to initial GNP per capita across countries as well as to the average rate of growth of output per head 1965-1998, with or without adjustment for the level of initial output (Figure 2). The observed cross-country relationship between depreciation and investment is also positive. One of our aims is to suggest possible explanations for these patterns.

**Table 1.** Determinants of Economic Growth

| Variable | Coefficient |
|---|---|
| Constant | 11.1<br>(7.3) |
| Initial income | -1.65<br>(8.6) |
| Rate of growth of population | -0.84<br>(5.4) |
| Log of secondary-school enrolment rate | 0.63<br>(2.4) |
| Natural capital share | -0.06<br>(4.5) |
| Net investment rate | 0.10<br>(3.7) |
| Depreciation rate | 0.28<br>(4.8) |
| $R^2$ | 0.74 |
| Observations | 85 |

Note: t-statistics are shown within parentheses.

Table 1 shows the results we get when we regress economic growth per capita on its main determinants according to standard theory and practice – that is, on initial income (to account for catch-up and convergence), population growth (to account for the population drag in the Solow model of medium-term growth), education (measured by the logarithm of the secondary-school

[2] Depreciation refers to consumption of fixed capital and represents the replacement value of capital used up in the process of production. The data are taken from the United Nations Statistics Division's *National Accounts Statistics: Main Aggregates and Detailed Tables, 1997*, extrapolated to 1998.

enrolment rate to account for diminishing returns to education), natural capital (in proportion to national wealth,[3] to account for the effects of rent seeking, the Dutch disease and more), and last but not least gross domestic investment (net investment and replacement investment separately[4]). The table shows that every one of these explanatory variables makes an economically and statistically significant contribution to growth in our sample of 85 countries over the period 1965-1998.[5] Notice, in particular, that the regression coefficient of depreciation – i.e., replacement investment – is almost three times as large as the coefficient of net investment.[6] This contradicts standard practice which is to assume that net investment and replacement investment have identical effects on economic growth. We take this finding to suggest that the relationship between economic growth and depreciation may be more involved than hitherto assumed. Accordingly, we intend here to explore the analytical relationship between depreciation and some of the other determinants of economic growth as well as growth itself. The empirical relationship between depreciation and growth awaits further scrutiny in future work.

Quality, as we define it, will turn out to be closely related to depreciation – due to economic obsolescence or physical wear and tear. Physical depreciation is a technological phenomenon. A tractor wears out with normal use, and ultimately breaks down because, with time, individual parts break or fail to function. By economic depreciation we mean obsolescence. Even if it may be technologically feasible to keep a tractor in running order for decades on end, it ceases to make economic sense at some point because the upkeep ultimately becomes too expensive compared with the cost of a new and better tractor (Scott, 1989). In growth theory, depreciation has traditionally been taken to be almost a constant of nature that affects the steady-state level of capital and output per head and medium-term growth in the Solow model and the long-run rate of growth of output per capita in endogenous-growth models, but it has not been presented as one of the movers or shakers of economic growth.[7]

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[3] See World Bank (1997).

[4] Net investment is calculated as gross investment minus depreciation.

[5] A detailed discussion of the sample and data is provided in Gylfason and Zoega (2001). The main emphasis there is on the link between natural capital and economic growth through investment.

[6] The coefficients of net investment and replacement investment in Table 1 are significantly different from one another according to a Chow test ($F = 9.3$, $p = 0.003$).

[7] To take one example, Aghion and Howitt (1998, p. 111) postulate that increased depreciation will have an ambiguous effect on growth because in the short run it reduces the real rate of interest – which tends to increase the incentive to undertake research – while, on the other hand, it directly reduces the rate of change of the per capita capital stock. Thus, capital accumulation slows down while lower interest rates drive innovators to new highs. This is the sole mention of the relationship between depreciation and growth that we could find in a book of almost 700 pages. The recent book by Barro and Sala-i-Martin (1995) does not list depreciation in its index.

As the quotes at the beginning of the paper attest, producers of capital equipment have considerable leeway in deciding the durability of the equipment. Decision-making on the optimal level of planned obsolescence is taught in business schools. We will look at this optimisation problem from a macroeconomic standpoint by deriving the optimal level of quality – that is, the one that maximises either consumption in steady state or the rate of growth of output – and relating this to factors such as saving and investment rates and economic growth. The direction of causation can go either way. At last, we will try to assess whether it is likely that a market economy be dynamically inefficient because private firms choose a level of quality of capital that is suboptimal from a macroeconomic or social standpoint.

We proceed, in Section I, by defining terms and preparing the groundwork for our analysis. In Section II we derive the optimal levels of depreciation and durability in two commonly used models of economic growth. In Section III we study quality decisions at the microeconomic level in an attempt to assess the likelihood that a market economy yields the optimal level of quality from a macroeconomic point of view. Section IV offers some concluding remarks.

## I. Productivity and Durability

We think of quality in two dimensions, *productivity* and *durability*. These can be quite distinct: a piece of capital can do well on one level and not on the other. While we take productivity to be an exogenous variable for most of our analysis, durability is endogenous throughout. When investing, firms decide on the level of spending needed to plan for, organise and ensure durability of the new capital equipment. By spending more at the time of investment, they can make the capital last longer. Thus, there arises a trade-off: by spending more on a given investment, firms need to spend less replacing worn-out or obsolete capital later on.

### Type I quality: *Productivity*

Quality reflects the average productivity of capital. Thus, a low-productivity unit of capital is only partially usable in production because it has been allocated to inefficient uses or because it is old, whereas a high-quality unit is completely usable. We measure quality – that is, average productivity – by an index $q$ that goes from zero (not usable at all) to one (completely usable).

Examples include machines that can only be used a few hours each day due to costly and time-consuming maintenance procedures. Imagine an aeroplane that requires many hours of maintenance on the ground for every hour in flight (e.g., the Concorde). Another example is capital equipment that is virtually useless, such as the concrete bunkers scattered all across Albania under Enver Hoxha. We would give them a value of close to zero on our quality index. Even so, these bunkers are of high quality in the sense of being almost indestructible. This leads to our second definition of quality:

**Type II quality: *Durability***

Quality mirrors the durability of capital. A low-quality unit of capital is one that is not going to last very long while the highest quality brings maximum durability. We measure durability by an index $d$ that goes from zero to one.

In this case, the bunkers of Mr. Hoxha come out near the top of the list, for despite low productivity they have indeed proved durable. Modern computers, by contrast, can be very productive if used wisely, but they are not very durable due to their rapid obsolescence.

We have seen that productivity ($q$) and durability ($d$) do not always have to go hand in hand. The pyramids of Egypt were a high-productivity investment in their day – good at preserving mummies! – and they have lasted a long time (high $q$, high $d$); they remain among Egypt's major sources of foreign exchange. High-quality computers, on the other hand, do not last very long because they are quickly rendered obsolete by better machines (high $q$, low $d$). Soviet housing, which sometimes began to crumble even before construction was completed, is an example of low-productivity, low-durability investment (low q, low d). And finally, the remarkable bunkers of Mr. Hoxha's regime in Albania, hundreds of thousands of them, were built to last as long as the pyramids but have, at least so far, been utterly useless (low $q$, high $d$).

We now proceed to derive the optimal level of durability using the Solow model. We then move on to a simple endogenous-growth model of the *AK* variety (the Romer model) and derive the level of durability that maximises the rate of growth of output. Finally, we model the decision by firms on the durability of capital equipment and discuss whether it is likely that a market economy will generate a level of durability and depreciation that is optimal from a macroeconomic or social viewpoint.

## II. The Optimal Durability of Capital

In this section we derive optimality conditions for durability in two commonly used models of growth: (a) the Solow model and (b) an endogenous-growth model with learning-by-doing and knowledge spillovers.

## II.1. The Solow Model

We use the Solow model to describe the determination of steady-state output and capital under diminishing returns to capital. We augment the standard model to take quality into account – both productivity and durability as defined in Section I.

Output is produced with labour and capital

$$Y = F(qK, L) = (qK)^{1-\alpha}(AL)^{\alpha} \tag{1}$$

Here $Y$ denotes output, $L$ is employment, $qK$ is the effective stock of capital where $q$ is our productivity index, $K$ is the gross stock of capital, $A$ is the level of labour-augmenting (or Harrod-neutral) technology, and $1 - \alpha$ is the elasticity of output with respect to capital. The production function can be rewritten in intensive form as

$$y = f(qk) = (qk)^{1-\alpha} \tag{2}$$

We normalise output and capital by the number of efficiency units of labour: $y = Y/AL$ and $k = K/AL$. In long-run steady-state equilibrium, the growth of output must equal population growth plus the rate of labour-augmenting technological progress.

Physical depreciation $\delta$ is assumed to be a decreasing function of the durability $d$ of the capital stock:

$$\delta = (1-d)^{\beta} \tag{3}$$

where $\beta > 1$ ensures diminishing returns to durability. Thus, the more durable the capital stock, the less rapidly it depreciates. When $d$ rises from zero to one, $\delta$ falls from one to zero. However, durability comes at a cost. A fraction $d$ of total investment expenditures is used to ensure the durability of the installed capital equipment; the rest (i.e., the fraction $1 - d$ of the total) is available for the accumulation of fresh capital. For example, when $d = 0.3$ and $\beta = 9$, then $\delta = 0.04$.

Saving is equal to gross investment and is proportional to output: $sY = I_g$ where $s$ is the saving rate. The dynamics of capital accumulation can now be described as follows:

$$\dot{k} = i_g(1-d) - [\delta(d) + n + \lambda]k \tag{4}$$

Here $i_g$ denotes gross investment per augmented labour unit, $n = \dot{L}/L$ is the rate of population growth, and $\lambda = \dot{A}/A$ is the rate of labour-augmenting technological progress. We use $di_g$ to denote the number of units of the capital good used up in attaining a durability level $d$ for new capital units that number $(1\text{-}d)i_g$.

In the steady state where $\dot{k} = 0$ we have

$$\left[f(qk) - c\right](1 - d) = \left[\delta(d) + n + \lambda\right]k \tag{5}$$

Notice that $c = y - i_g$ is consumption per efficiency unit of labour, or

$$c = f(qk) - \left[\frac{\delta(d) + n + \lambda}{1 - d}\right]k \tag{6}$$

To find the optimal quantity of capital and its optimal durability we now maximise consumption per unit of augmented labour with respect to $k$ and $d$. We start with the quantity of capital.

***The Optimal Capital Stock***

The optimal capital stock $k^*$ is the solution to[8]

$$qf_k(qk) = \frac{\delta(d) + n + \lambda}{1 - d} \tag{7}$$

The left-hand side of the equation shows the marginal benefit of having one more unit of capital (this is simply the marginal product of capital), while the right-hand side shows the marginal cost of maintaining this extra unit in the face of depreciation, population growth and technological progress. Equation (7) can be used to derive the optimal saving rate as follows:[9]

$$\frac{qf_k k}{y} = \frac{(\delta + n + \lambda)}{1 - d}\frac{k}{y} = \frac{i_g}{y} = s \tag{7'}$$

or, given equation (3),

$$s = \left(\frac{k}{y}\right)\left[\delta^{1-\frac{1}{\beta}} + (n + \lambda)\delta^{-\frac{1}{\beta}}\right] \tag{7''}$$

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[8] It can be shown that $\beta \geq 2$ is enough but not necessary for the second-order condition for a maximum to be satisfied.

[9] This can be rewritten as

$$\frac{qf_k k}{y} = \frac{profits}{y} = s$$

which gives the Golden Rule of saving as stated by Phelps: "Save profits and consume wages."

In the long run, the optimal saving rate is simply $1 - \alpha$, the standard result. Hence, equation (7”) tells us that (i) an increase in $n$ or $\lambda$ must reduce the capital/output ratio in the long run and (ii) an increase in the depreciation rate $\delta$ will similarly reduce the capital/output ratio in the long run as long as $\beta > 1 + (n + \lambda)/\delta$ (more on this condition below). This inverse relationship between the optimal capital/output ratio and depreciation thus follows from our assumption of diminishing returns to durability.[10]

Equation (7) gives the *Golden Rule of accumulation*. It describes the long-run equilibrium growth path that maximises consumption per augmented labour unit in all periods. If an increase in saving is required to move to the golden path, the present generation would have to sacrifice consumption for the benefit of future generations of consumers.

The golden-rule level of capital $k^*$ depends on both the productivity and durability of capital. The higher is durability, $d$, the more expensive, in terms of consumption foregone, is the maintenance of the capital stock for a given rate of depreciation. In other words, the more durability, the greater the sacrifice needed to maintain it for given depreciation. This effect appears in the denominator of the right-hand-side term of equation (7) – the higher $d$, the larger is the ratio and the lower is the optimal capital stock. However, durability also reduces the depreciation rate and hence also the numerator on the right-hand side of the equation. The net effect of durability on the golden-rule capital stock $k^*$ is, therefore, ambiguous.

Let us be more precise. We can show by taking the total differential of equation (7) that increased durability will raise the optimal level of the capital stock if the following condition holds:

$$\beta > 1 + \frac{n + \lambda}{\delta} \tag{8}$$

The $\beta$ on the left-hand side of the equation is a measure of the effect of durability on depreciation. A high value of $\beta$ implies that with a more durable capital stock there is less need for replacement investment, making it less costly to maintain a given level of capital. This increases the optimal level of capital. However, as captured by the terms on the right-hand side of the equation, increased durability comes at a cost. First, it costs more to replace the units of capital that do depreciate in spite of greater durability and this is captured by the number one on

[10] More precisely, our assumption of diminishing returns to durability is a necessary but not sufficient condition for a negative long-run equilibrium relationship between the depreciation rate and the optimal capital-output ratio as shown in equation (7”).

the right-hand side. So, in the absence of population growth and technological progress we would need $\beta > 1$ for more durability to increase the optimal capital stock. With population growth and technological progress we also have to take into account – this is captured by the last term on the right-hand side – that increased durability makes it more costly to produce capital equipment to satisfy a growing and increasingly productive population.

The effect on $k^*$ of changing the productivity parameter $q$ turns out to be ambiguous as well. First, for a given number of efficiency units of capital $qk$, the higher is $q$, the greater the gains from investing. But for a given level of $k$, the higher is $q$, the lower is the marginal product of capital. So, the net effect on $k^*$ of changing $q$ is also ambiguous. A more efficient economy – that is, an economy with more productive capital – may have either more or less capital when steady-state consumption is at a maximum.[11]

***The Optimal Level of Durability***

From equations (6) and (3) we can derive the first-order condition for optimal durability $d^*$ as:

$$\frac{(1-d)^{\beta}+n+\lambda}{(1-d)^{2}}k = \frac{\beta(1-d)^{\beta-1}}{1-d}k \tag{9}$$

The left-hand side shows the marginal cost of increasing durability $d$. This is the increase in the cost of replacement investment – units of output used up in building up durability – that is needed every year. The right-hand side represents the marginal benefit that consists of a lower rate of depreciation in long-run equilibrium, i.e., fewer units of capital need to be replaced each year. So, with a more durable capital stock, there are fewer units of capital that need to be replaced, but replacing each unit is more costly in terms of consumption foregone.[12]

The marginal benefit in equation (9) depends on the parameter $\beta$ that shows the effect of durability on the depreciation rate; see equation (3). The greater the effect of investing in durability on depreciation, the higher is the optimal level of such investment. Notice also that the capital stock appears on both sides of equation (9). Therefore, the optimal level of durability does not depend on the level of the capital stock, and is given by

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[11] The effects of population growth $n$ and technological progress $\lambda$ are standard; both reduce the optimal level of the capital stock.

[12] When we allow for different vintages of the capital stock (Nelson, 1964) so that older units of capital are less productive than more recent ones, we find that there is an additional cost of raising the value of $d$: more durability raises the average age of the capital stock, and hence reduces average productivity. For this reason, the optimal level of durability is lower than that implied by equation (9); see equation (10).

$$d = 1 - \left[\frac{n+\lambda}{\beta - 1}\right]^{\frac{1}{\beta}} \tag{10}$$

As long as $\beta > 1$, the optimal level of durability varies inversely with population growth and technological progress. Hence, as $n + \lambda$ rises, the optimal rate of depreciation also rises:

$$\delta = \frac{n+\lambda}{\beta - 1} \tag{11}$$

Given our assumption that $\beta > 1$, we have here a positive relationship between optimal depreciation and long-run economic growth in the Solow model. When the rate of population growth is high or the rate of technological progress is high, it is costly to maintain a high-quality capital stock as each unit of capital costs more to install. This is also the reason why both rapid population growth and rapid technological progress cause the optimal level of capital (per unit of augmented labour) to be low. It follows that increased population growth or technological progress causes both the quantity and quality of capital to drop in the long run.[13] Going back to our earlier examples, it is perhaps not surprising that the rate of depreciation or obsolescence is high in the case of computers or housing in the former Soviet Union, the main reason being technological progress in the former case and the need for rapid reconstruction after the Second World War (as well as stringent rent controls, we presume) in the latter, while Hoxha's bunkers and the Egyptian pyramids were built under different conditions.

The total effect of a change in population growth or technological progress on the optimal stock of capital now consists of both the direct effect on the quantity of capital $k$ and the indirect effect through durability. By taking the total differential of equation (7) we see that the indirect effect vanishes when $\beta = 1 + (n + \lambda)/\delta$ (optimal depreciation), reinforces the direct effect when $\beta > 1 + (n + \lambda)/\delta$ (too much depreciation) and offsets the direct effect when $\beta < 1 + (n + \lambda)/\delta$ (too little depreciation). Under certain conditions – namely, a high value of $\beta$ – the total effect of a rise in population growth or technological progress on the level of steady-state capital per

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[13] We could also let technological progress influence depreciation and obsolescence directly by replacing equation (3) by, say, $\delta = (1 + \lambda - d)^{\beta}$. Then equation (9) becomes $\frac{(1+\lambda-d)^{\beta} + n + \lambda}{(1-d)^2}k = \frac{\beta(1+\lambda-d)^{\beta-1}}{1-d}k$. Now a change in $\lambda$ increases not only the marginal cost of durability on the left-hand side of the new version of equation (9) like before but also the marginal benefit of durability on the right-hand side of the equation. Therefore, the net effect of technological progress on durability and hence also on depreciation is ambiguous in this case.

person is larger than the direct effect because the indirect effect operating through the depreciation rate reinforces the direct effect.

### II.2. Endogenous Growth

The Romer (1986) model of economic growth postulates constant returns to capital due to learning-by-investing and instantaneous knowledge spillovers. The aggregate production function is now

$$Y \;=\; BL^{\alpha}\left(qK\right)^{1-\alpha} \tag{12}$$

$L$ denotes raw labour and $q$ represents the quality of capital as before. Technology is assumed proportional to the capital/labour ratio:

$$B \;=\; E\left(\frac{qK}{L}\right)^{\alpha} \tag{13}$$

This implies that output is proportional to quality-adjusted capital:

$$Y \;=\; qEK \tag{14}$$

where $E$ represents efficiency. As before, net investment $\dot{K}$ equals $(1-d)I_g - \delta K$ and saving $sY$ equals gross investment $I_g$, so the rate of growth of output and capital $g \;=\; \dot{Y}/Y = \dot{K}/K$ is now

$$g \;= sq(1-d)E \;-\; \delta\left(d\right) \tag{15}$$

and $\delta = (1-d)^{\beta}$ as before. Maximising growth with respect to durability we get[14]

$$sqE \;=\; \beta\left(1-d\right)^{\beta-1} \tag{16}$$

which implies that

$$d \;=\; 1-\left(\frac{sqE}{\beta}\right)^{\frac{1}{\beta-1}} \tag{17}$$

and

$$\delta \;=\; \left(\frac{sqE}{\beta}\right)^{\frac{\beta}{\beta-1}} \tag{18}$$

[14] The second-order condition for a maximum is satisfied: $dg/dd \;=\; -\,\beta\left(\beta\,-1\right)\left(1-d\right)^{\beta\,-\,2} < 0.$

Equation (15) shows that too much durability as well as too little durability is detrimental to growth. The key to optimal durability is to minimise the cost of maintaining the capital stock, which is the sum of the cost of ensuring durability and capital lost through depreciation. Given our assumption that $\beta > 1$, we have here a positive relationship between the optimal rate of depreciation and the saving rate (recall Figure 2). Substituting the solutions for optimum durability and depreciation from equations (17) and (18) back into the growth equation (15) gives

$$g = \left[ (\beta - 1)\beta^{-\frac{\beta}{\beta - 1}} \right] (sqE)^{\frac{\beta}{\beta - 1}} \tag{19}$$

or, using, equation (17),

$$g = (\beta - 1)\delta \tag{20}$$

Hence, economic growth varies directly with depreciation as in Figure 2 as long as we have diminishing returns to durability ($\beta > 1$). More importantly, equation (20) shows that the reactions of economic growth and depreciation to changes in their underlying determinants (saving behaviour, productivity and efficiency) are qualitatively similar as long as $\beta > 1$.

At the optimum, the sum of the two kinds of cost is minimised and the rate of growth is maximised. Initially, investing in durability brings benefits that outweigh the costs because depreciation is much reduced. However, as we keep increasing durability further we will find that the gain in terms of a further fall in the rate of depreciation becomes smaller. So, there comes a point at which a further increase in durability is suboptimal.

From equation (17) it follows that the optimal level of durability is decreasing in the saving rate $s$ as well as in productivity $q$ and efficiency $E$. A higher saving rate, more productivity $q$ and greater efficiency $E$ all raise the marginal cost of raising durability and thus reduce its optimal level. Therefore, the higher the saving rate or productivity or efficiency, the lower is the level of durability and the higher is the rate of depreciation. The intuition behind this effect is similar to the reason why growth affects optimal durability adversely in the Solow model: when the saving rate rises, the cost of maintaining durability in the expanding capital stock is higher and hence the optimal level of durability is lower.

## III. Does the Market Economy Deliver Optimal Durability?

The quotation at the beginning of this paper describes a real-world decision problem facing firms concerning the durability of output. The question now arises whether firms in a market economy choose the socially optimal level of durability as derived in the two models above. In particular, we now imagine that an economy is moving along an optimal path when it comes to saving and capital accumulation and allow profit-maximising firms to decide on the level of durability of the capital goods. We are interested in whether the profit-maximising level of durability will be the same as the socially optimal one.

Increasing durability in the production of capital goods brings two types of private costs. First, raising durability is likely to cause the cost of production to go up and hence reduce current profits. Second, higher durability reduces the probability that the customer – who is the owner of the capital equipment by assumption – returns to buy a replacement unit. So is there then any imaginable private benefit from ensuring the durability of one's product?

A clear private benefit from increasing durability is an increase in customer satisfaction. Producing junk is not likely to create many satisfied customers and a dissatisfied customer is not likely to return. So one can think of the decision on durability as an investment decision where the investment is in future market share. Producing high-quality goods is then likely to increase one's market share as the word spreads from an expanding base of satisfied customers. High quality may thus turn out to be a good policy in the long run.

We model these intertemporal trade-offs within the customer-market model of Phelps and Winter (1970).[15] The term customer market is used for a product market where there is no auctioneer setting prices to clear the market. Rather, firms set prices and information about each firm's prices gradually filters through the market, passed on from one customer to another. Information frictions in the market cause customers to form an attachment to a given supplier until he or she learns of better offers – lower prices or, in our context, higher quality – elsewhere. Due to these information frictions, a firm's customer base or market share becomes an asset that can be exploited through high prices or low quality or both. We can thus raise current profits by charging higher prices or selling shoddier goods but only at the cost of

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[15] An early predecessor of Phelps and Winter is the 13$^{th}$-century writer Saint Thomas Aquinas who writes about quality and information about quality in *Summa Theologica*, as reproduced in Monroe (1924, p. 61). According to Saint Thomas a seller must not knowingly sell a defective product and if some defective product is by accident passed along, the seller must compensate the buyer when the fault is discovered. Also, the seller must admit to an imperfection in an otherwise acceptable product. Needless to say, if firms were to follow this saintly advice the

gradually losing our market share as our customers turn to other sellers. A trade-off arises between current and future profits. Raising prices and reducing quality increases profits today at the cost of lower profits in the future. Competition in customer markets does not rigidly ensure a single price since the buyer and the seller do not observe all prices set in the market. If a supplier chooses to cut prices, customers elsewhere do not immediately know about this action. Only gradually will the news spread and attract new customers. Therefore, it is costly for firms to gain new customers. As a result, the equilibrium price is above the competitive equilibrium price level in a customer market. The price exceeds the unit cost of production yielding a pure profit in equilibrium.

The customer-market theory can be applied to quality as well as price. Just as the firm contemplating a reduction of its price below the average going price in the industry knows that it could not communicate the good news costlessly and quickly to customers at other firms, so, likewise, the firm contemplating a better product could not costlessly and immediately penetrate the consciousness of the entire market with the news of the product improvement. The firm might even have to persuade consumers that it is not lying, not hiding the knowledge that it is not really offering a better product. Thus, information frictions in customer markets impede the competitive drive toward higher quality as well as lower prices. In other words, customer markets stop short of offering all the product improvements that would be demanded by informed consumers despite greater production costs because of the transaction cost of informing, and in some cases convincing, interested consumers of the improvement. Therefore, only the improvements that are easy to describe and demonstrate to consumers have any chance of being marketed successfully; of these, the improvements that are biggest compared with their production cost have the best chance. For example, improvements in automobile fuel requirements may have nearly as good a chance of reaching the consumer as a price cut, but improvements in tire reliability or braking defect rates would be more difficult to market.[16]

The representative capital-producing firm's optimisation problem is described below. We model the behaviour of a capital-goods producer who supplies customers in an imperfectly

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customer-market model would miss the mark.

[16] The customer-market model supports the case for regulation to control quality. The government requires that products and production methods meet certain specifications. It is possible to enact and enforce laws against false and misleading advertising. That way the government can increase the information value of advertising by firms attempting to market a safer, better or cheaper product. It is also possible for the government to grade goods, classify or categorise them. By that device the government makes it easier for firms to advertise that they have a better product by flaunting its government rating.

competitive market – due to information frictions – and uses *xK* units of capital where *K* is the aggregate capital stock in the economy and *x* is the representative firm's market share and lies between zero and one. Aggregate demand for new capital goods equals $(\delta + n + \lambda)K$ in long-run equilibrium for the economy as a whole where $\delta$, *n* and $\lambda$ denote depreciation, population growth and technological progress as before and $(\delta + n + \lambda)Kx$ is the demand for the representative firm's output.

We assume that firms can convert a unit of final-goods output into a unit of capital at no cost short of the cost of making the capital equipment durable. As in the Solow model and the Romer model we assume that a fraction *d* of the cost of investment is used to ensure the durability of the new capital equipment. The rest (i.e., the fraction $1 - d$ of the total) is available for the accumulation of fresh capital. Therefore, the unit cost of producing capital is equal to $1/(1 - d)$. The current profit from producing a unit of capital equipment can then be written as the difference between the price and unit costs: $p - 1/(1 - d)$.

The representative firm's optimisation problem can now be described as follows:

$$\underset{p,d}{\text{Max}} \int_0^\infty \left[ \left( p - \left( \frac{1}{1-d} \right) \right) \left( \delta(d) + n + \lambda \right) K \right] x e^{-rt} \, dt \tag{21}$$

$$\text{s.t.} \quad \dot{x}K = \dot{x}K = \phi(p,d)xK, \quad \phi_1 < 0, \ \phi_{11} < 0, \ \phi_2 > 0, \ \phi_{22} > 0$$

$$\delta = (1-d)^\beta$$

where *r* is the exogenous real rate of interest. The firm sets the price of the capital equipment *p* and decides the level of durability of the equipment *d*. The market share *x* is a state variable that is inherited from the past but can be changed gradually by the firm's policy on price and durability: lowering prices and furthering durability (i.e., increasing quality) are both likely to expand the market share in the future.

Before moving further, let us now derive the optimal levels of durability in this model as calculated by a hypothetical central planner. This can be found by minimising the expression $(\delta(d) + n + \lambda)K/(1 - d)$, which is the cost of maintaining the level of capital *K*. The first-order condition is

$$\frac{(1-d)^\beta + n + \lambda}{(1-d)^2} K = \frac{\beta (1-d)^{\beta - 1}}{1-d} K \tag{22}$$

and is identical to equation (9) in the Solow model. The left-hand side is the marginal cost of increasing durability, in the form of a higher cost of investing. The right-hand side is the marginal benefit, in the form of less depreciation, and hence a lesser need for replacement investment. Taking the total differential of equation (22) gives the effect of changes in population growth and technological progress on optimal durability:

$$\frac{dd}{dn} = \frac{dd}{d\lambda} = -\frac{1}{\beta(\beta-1)(1-d)^{\beta-1}} \tag{23}$$

which is negative as long as $\beta > 1$. Thus, with diminishing returns to durability, the optimal level of durability varies inversely with population growth and technological advance.[17]

The managers of the representative firm differ in two fundamental ways from the central planner. First, they have market power in the market for capital goods and set prices to maximise profits and, second, they have to consider the effect of their actions on their future market share.

The solution to the optimisation problem (21) consists of a set of conditions that have to be satisfied along an optimal path. As in Section II, we will only describe the steady-state conditions and leave the transition towards this steady state out of our analysis. We start with the condition that gives the optimal price:

$$(1-d)^{\beta} + n + \lambda = -\mu\phi_1(p,d) \tag{24}$$

where $\mu = \frac{1}{r}\left\{\left[p - \left(\frac{1}{1-d}\right)\right](\delta + n + \lambda)\right\}$ is the shadow price of a customer in the steady state with a fixed and exogenous rate of interest – this is, the present discounted value of profits per customer – and $\phi_1$ is the partial derivative of the customer-flow equation with respect to prices. Profits per unit sold equal $p - 1/(1-d)$ while profits per customer can be written as $(p - 1/(1-d))(\delta + n + \lambda)$. The left-hand side of equation (24) shows the marginal benefit of raising prices, in the form of higher current profits. The right-hand side shows the marginal cost, in the form of lost market share due to these higher prices. The right-hand side of the equation thus measures the impact of raising current prices on future profits. When $\phi_1$ has a

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[17] If we allow technological progress to affect the rate of depreciation and obsolescence directly, so that $\delta = (1+\lambda-d)^{\beta}$, then a change in $\lambda$ has an ambiguous effect on optimal durability $d$ as equation (23) now becomes $\frac{dd}{d\lambda} = -\frac{1+\beta(1+\lambda-d)^{\beta-1} - \beta(\beta-1)(1+\lambda-d)^{\beta-2}(1-d)}{\beta(\beta-1)(1+\lambda-d)^{\beta-2}(1-d)}$.

high (absolute) value, the market share is going to shrink rapidly which results from a rapid flow of information between customers.

A similar condition gives the optimal level of durability

$$-\beta(1-d)^{\beta-1}\left(p-\frac{1}{1-d}\right)-\frac{(1-d)^{\beta}+n+\lambda}{(1-d)^{2}} = -\mu\phi_2(p,d) \tag{25}$$

The left-hand side shows the marginal cost of raising durability. This takes the form of fewer customers returning to replace worn-out capital goods (first term on the left-hand side) and current profits falling because of a higher cost of production (second term on left-hand side). The right-hand side shows the marginal benefit of raising durability, in the form of higher future profits due to an expanding market share.

Consider now the effect on current profits on the left-hand side of equation (24). Setting the shadow price of customers $\mu$ to zero, we can rewrite equation (24) thus

$$\frac{(1-d)^{\beta}+n+\lambda}{(1-d)^{2}} = -\beta(1-d)^{\beta-1}p+\beta(1-d)^{\beta-1}\left(\frac{1}{1-d}\right) \tag{26}$$

Notice that the left-hand-side term and the second term on the right-hand side are the same as in equation (22). The former is the marginal cost of raising durability in terms of higher production costs. The latter is the marginal benefit in terms of lower costs of production for customers returning to renew their capital equipment. But now there is a new term on the right-hand side. This is the fall in revenue that occurs when the number of returning customers falls. Equation (21) suggests that $p > 1/(1 - d)$ so that the sum of the two right-hand terms in equation (26) is negative. Therefore, the marginal benefit from increasing durability is always negative and the optimal level of durability is for that reason equal to zero in this static version of the model. Because current profits would be maximised by setting $d$ equal to zero, that is, by producing junk, the firm can make sure that customers visit frequently and it can satisfy their demand at a low cost. This contrasts with the central planner who does not choose this strategy because of the sacrificed output that would be used up producing new units of capital to replace those worn down each period. The representative firm does not mind since it can earn a profit on each unit sold.

However, once we take the intertemporal dimension of the problem into account, it becomes clear that such unscrupulous behaviour will result in a loss of market share in the longer run as customers drift away from the provider of the low-quality capital good. The intertemporal trade-off in equation (22) determines the level of durability and depreciation in this market economy with information frictions in the market for capital goods. When producers sacrifice current profits in order to make their products more durable they are investing in the goodwill of their customers, hoping that they will spread the word and help attract more customers.

Equation (25) tells us that firms should reduce durability until the marginal benefit in terms of current profits is equal to the marginal future loss in the form of a lower market share and a lower present discounted value of future profits. The resulting level of durability will depend on the nature of the information frictions, that is, the form of the customer-flow function $\phi$. In particular, the private and social optimum will be the same if and only if

$$p\beta\left(1-d\right)^{\beta-1} = \mu\phi_2(p,d) \tag{27}$$

which will make equation (25) – the condition for a private optimum – identical to equation (22) – the condition for a social optimum. There is no guarantee that this equation will hold so that the private optimum will only by chance coincide with the socially optimal levels of durability. In particular, if information spreads slowly in the market for capital so that news of quality improvements is not likely to be spread quickly to potential customers, this will result in limited durability because the benefits – in the form of an increased market share – will be limited. If, in contrast, the news spreads quickly, the level of durability is likely to be much higher.

What about the effect of population growth and technological progress? Clearly, an increase in either will increase the current cost of maintaining durability. With the population growing or technology progressing or both, there is more demand for capital equipment. With more production, it becomes more costly to produce and current profits will be smaller. Therefore, when we only take into account the effect on instantaneous profits, increased population growth or technological progress will act to reduce the profit-maximising level of durability. However, the shadow price of market share in equation (25) will also be higher because the market is expected to grow in the future. This makes firms pay greater attention to durability because doing so will help maintain and possibly expand their market share.

In sum, it is not clear whether a market economy will generate the socially optimal level of durability as defined by equation (22) or whether it will respond in a socially optimal way to changes in the rate of population growth $n$ and the rate of technological progress $\lambda$.

## IV. Conclusion

This paper is intended to shed new light on the relationship between depreciation, obsolescence and economic growth. In growth theory thus far, depreciation and obsolescence have been regarded as exogenous phenomena through some form of exponential decay. In the Solow model, more rapid depreciation reduces output and capital per head in the long run and hence also the rate of growth of output per head in the medium term (i.e., as long as it takes the capital/output ratio to settle at its long-run steady-state equilibrium value following an exogenous shock to the system). In the *AK* version of endogenous-growth models, as in the Harrod-Domar model, increased depreciation reduces the rate of growth of output per head even in the long run.

Our aim has been to see what happens to the relationship between depreciation and growth if the rate at which machinery and equipment wears out or is rendered obsolete is a matter of managerial choice. For firms do have a choice: they can either keep the current cost of investment down by skimping on quality and accepting more rapid depreciation or obsolescence as a result, or they can choose to incur a higher initial cost of investment in order to build durable capital that depreciates slowly. We described the representative firm's decision problem as involving a simultaneous but separable choice of the quantity and quality of capital in production where by quality we mean durability which, in turn, we take to be inversely related to depreciation.

This view of endogenous depreciation, including obsolescence, leads to some new propositions:

(a) Increased population growth accelerates depreciation given our assumption of diminishing returns to durability because providing a rapidly growing population with high-quality capital is costly in terms of consumption foregone, and thus slows down economic growth in the medium term more than it would if depreciation were exogenous. This result means that the population drag on medium-term growth is stronger in our model than in the Solow model. In the long run, the adverse effect of population growth on the level of output per head is reinforced.

(b) Increased technological progress also accelerates depreciation for an analogous reason given our assumption of diminishing returns to durability, and thereby stimulates medium-term growth less than it would if depreciation were exogenous. This means that more rapid technological advance increases the level of output per capita less than it would if depreciation were exogenous, even if long-run per capita growth remains unchanged and equal to the rate of technological progress.

(c) Increased saving accelerates depreciation in our endogenous-growth model given, once more, our assumption of diminishing returns to durability, thereby strengthening the positive effects of increased saving and investment on economic growth. This is because growth is the assumed maximand in this model and higher saving and investment raise the cost of maintaining high quality: increased saving speeds up depreciation because that way growth also speeds up. In our version of the Solow model, however, a change in saving does not affect depreciation, so that Solow's conclusion about the impact of increased saving on medium-term growth remains intact.

(d) Increased efficiency by whatever means – liberalization, privatization, stabilization, diversification, you name it – also increases depreciation in our endogenous-growth model given, once again, our assumption of diminishing returns to durability, thereby strengthening the positive effects of increased efficiency on economic growth, for the same reasons as in (c) above.

The notion of dynamic efficiency in terms of the accumulation of capital is well established in the literature on economic growth (Ramsey, 1928). Models with overlapping generations and finite horizons demonstrate that there is no guarantee that a market economy will generate the optimal capital stock, i.e., the stock of capital that maximises consumption or utility in long-run equilibrium (Blanchard, 1985). When the working population cares about consumption in retirement or expects a decline in labour income, excessive saving can result. Our analysis extends this literature by deriving conditions for the optimal durability or quality of the capital stock. We have shown that this depends on population growth and technological progress – as does the optimal stock of capital in the standard formulation of dynamic efficiency – and also on the saving rate in a model of endogenous growth. We have thus aimed to extend the notion of dynamic efficiency to cover the quality of capital.

Moreover, we have shown using the customer-market model that there is no guarantee that a market economy will generate the optimal quality of capital. Profit-maximising producers of capital equipment may prefer low-quality output because such planned obsolescence will bring customers back for replacement purchases and reduce production costs. However, concern about customer satisfaction and future market share is a countervailing force.

Our analysis calls for empirical work to test for dynamic efficiency in terms of the quality of capital. While excessive capital accumulation – in violation of the standard golden-rule results in terms of the quantity of capital – may not be likely, we conjecture on the basis of our analysis that empirical evidence of the violation of dynamic efficiency in the form of either deficient or, in some cases, perhaps even excessive quality might emerge from the data.

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