Technological Innovation in Community Housing Development: Barriers to Energy Efficiency

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Abstract

Community housing developers produce affordable housing and jobs for many residents of low-income neighborhoods through the rehabilitation of existing single and multi-family buildings. Typically operating as small, not-for-profits or community-based organizations, the vast numbers of community housing developers creates high coordinating costs of operating jointly to acquire the shared learning needed to implement new techniques, such as those involving energy efficiency. This paper presents a model of technology adoption that suggests that new profitable technologies will be adopted only with low probability and that strategic interaction between potential adopters further reduces the likelihood of adoption. These features result from the ability of potential adopters to postpone the bearing the costs of adoption of new technologies and their ability to share the knowledge of others who have adopted new technologies. These features are particularly characteristic of community housing developers.

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1. Introduction

The U.S. Department of Housing and Urban Development (HUD) defines affordable housing as housing that costs no more than 30 percent of an occupant's income. Included in the HUD definition of the cost of housing is the cost of the energy used to operate the housing. In one recent year (1989) over 5 million households (approximately 80% of poor householders) spent at least 30 percent of their annual income on rent and utilities, and approximately 3.5 million households (56% of poor householders) spent more than 50 percent of their income on rent and utilities. To place these observations in perspective, an average family with an annual income of $50,000 spent approximately 15 percent of its income on rent and utilities (Katrakis, Knight, and Cavallo: 1994).

The absence of housing that fits into HUD's definition of affordability arises both from high rents and high utility costs. Responding to the high rents as normal market signals, developers of housing have found numerous ways to expand the housing stock in urban areas. One approach that is particularly important to urban neighborhoods is the rehabilitation (rehab) of existing residential buildings. Rehab can be a low cost method of housing development. Often the cost of a substantial rehab in a city like Chicago is between $55,000 and $70,000 per unit for a multifamily building. Substantial rehab involves demolition of the existing interior of the buildings and starting reconstruction from the remaining outer shell. The cost of moderate rehab in a city like Chicago is often between $20,000 and $35,000 per unit in a multifamily building. Moderate rehab generally is able to be performed if the interior walls of the building are in serviceable condition. With the cost of new construction ranging from $95,000 and up, the rehab of structurally sound building is an economical way to expand a community's housing stock in response to high rents.

One of the prime sectors that has responded to the need for affordable housing in urban communities has been the non-profit sector. Often motivated by goals other than financial gain, the non-profit housing developers tend to be small and community-oriented. With tax-exemptions and a smaller profit requirement, the community housing developer is frequently able to produce housing units through the rehab of existing buildings at costs that permit affordable rents. By providing rental units at low cost, the community housing developers also go a long way in saving buildings from abandonment and preserving the character of urban neighborhoods.

Though community housing developers are frequently able to produce housing a relatively low cost, they are generally less able to produce housing that has a low operating cost. By depending on development managers that are often lack professional experience and by using less skilled workers, the housing units produced by community housing developers are frequently expensive to operate due to building envelope insufficiencies in insulation and air sealing, poor choice of component systems, and mismatching of building systems. Particularly by not incorporating current concepts of energy efficiency, community housing developers can create housing that is affordable to rent but not affordable to operate because of high utility bills.

It is a well-known that the housing market can be plagued with a problem of inability to directly observe the future operating costs of a housing unit. After walls are up and windows are in, an energy efficient apartment can look identical to an energy hog. This barrier to energy efficiency, however, does not explain why signaling devices that have been developing in the new construction market have not carried over to the urban rehab market where the benefits of energy efficiency can be much greater. Possibly a more important barrier to the adoption by community housing developers of techniques that would lower energy costs in the strategic interaction associated with shared learning.

In this paper a model of technology adoption is developed that is based on optimizing behavior by potential adopters. The model considers technologies that require sunk costs in switching from an older technology. One likely source of such sunk costs are the training or other human capital costs associated with planning, managing, and successfully executing a new technology or technique. Any training costs directly connected to a new technique will almost certainly be sunk and unrecoverable if the project is not productive. The optimizing individual will generally react to the presence of sunk costs by requiring a higher profit margin to motivate investment in situations where the investment can be postponed (Dixit and Pindyck: 1994).

The possibility of postponement - waiting to bear costs for at least one additional period - becomes a more important factor in the decision process if shared learning is possible. Shared learning would occur whenever the training and other human capital costs of production are less for an individual who waits for another to bear those costs and thus lessen his own. Community housing developers may well be characterized as a group that learns best in a social setting by watching others accomplish some task rather than learning privately through research and introspection. The model developed here emphasizes share learning as a source of a barrier to the adoption of innovations.

In the next section, the basic optimization model is created and several characteristics derived. In the third section of the paper, the shared learning and strategic interaction is examined.

2. Technology Adoption under Monopoly

The basic problem of technological innovation for a decision-maker is to chose between continuing to use the technology that has been used in the past or to start using an alternative technology. This problem may be represented as the choice between two stochastic processes with the processes being alternative profit streams over future periods. Two essential differences between the two processes are that (1) there is less uncertainty associated with the profit stream of the old technology, and (2) that there is an unrecoverable cost of change - a sunk cost - associated with switching to the new technology. Here we focus on the second.

In this section, a model of technology choice is developed in which a profit-maximizing, risk neutral monopolist must choose between one technology that is currently being used and a new technology. It is assumed that annual profits from each technology are uncertain. Included in the costs of the new technology are the sunk costs of switching to that technology. An important part of the sunk costs in technology adoption is acquiring the human capital to implement the new technology, and the costs of acquiring this human capital will vary from period to period. Thus the sunk costs of switching to the new technology is itself a stochastic process. Because a potential adopter has the ability to delay the adoption of the new technology, the presence of the stochastic sunk costs becomes an important factor. We will see that the stochastic sunk costs create a hurdle that the new technology must surmount before the monopolist will switch away from the old technology. The hurdle is a required profit margin above mere equality between the new technology's discounted expected profit stream and that of the discounted expected profits of the old technology.

The model of the monopolist's choice between the two technologies is based on a model of choice under uncertainty. To concentrate our attention on the essential issues, we will assume that sunk switching costs for a period (x_t) are revealed at the start of the period and know to the decision-maker at the time of choice. The profits from the old technology for the current period (Π_{ot}) and all future period will be assumed to be revealed after the current period's choice is made. Similarly, the profits from the new technology minus switching costs (Π_{nt}) will be assumed to be revealed after the current period's choice is made. We will assume that the random variables Π_{ot} and Π_{nt} are bounded and time-invariant.[1] The expected profits for any one future period from the old technology are $E[\Pi_o]$, and the expected profits minus any switching costs from the new technology are $E[\Pi_n]$. We assume that the random variable x_t is bounded and has the time-invariant probability distribution function $F(x_t)$. Given the revelation of the the switching costs at the beginning of period t, the expected current period profits from the new technology are $E[\Pi_n]-x_t$. Since switching costs are a one-time event and assuming that the monopolist continues to use the new technology throughout the future, the discounted expected profit stream from the new technology may be defined as a function $\phi(x_t)=\sum_{\tau\in T}\beta^{\tau-t}E[\Pi_n]-x_t$, $T=\{t,t+1,t+2,\ldots\}$. β is the discount factor and is between zero and one. We assume Π_o, Π_n, and x_t are independent.

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[1] Because Π_{ot} and Π_{nt} are assumed to be time-invariant, we will exclude the time subscript hereafter.

We formulate the optimization problem of the individual as a choice between terminating the use of the older technology by accepting the current value of the cost or continuing the use of the older technology for at least one more period while awaiting the next realization, x_{t+1}, of the stochastic process. This maximization problem can be given as the dynamic programming functional equation, Eq. 1.

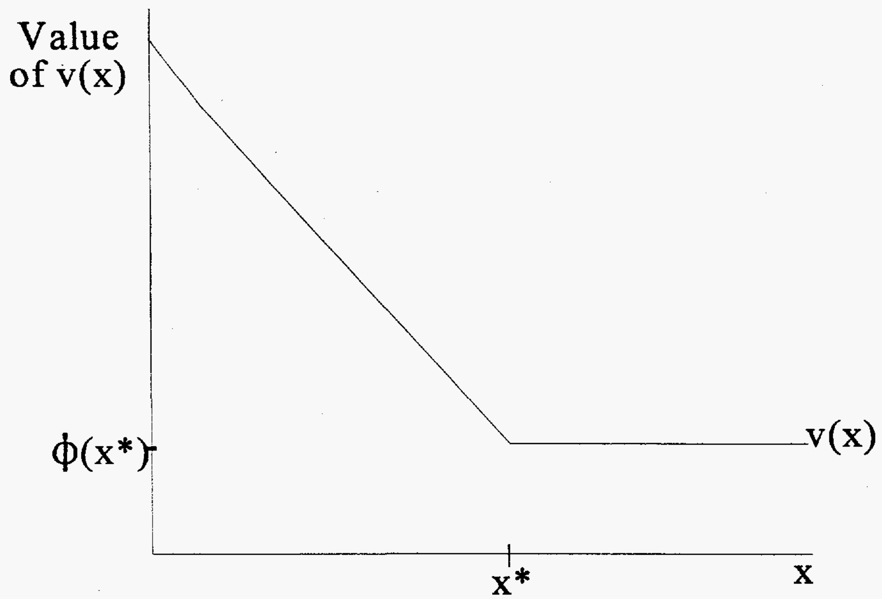
(1) $v(x_t) = \max\{\phi(x_t),\ E[\Pi_o] + \beta\int v(x_{t+1})dF(x_{t+1})\}$

The choice represented in the optimization problem depends on the current realization of the switching costs of the new technology. We observe that since $\phi(x_t)=E[\Pi_n]-x_t$, $\phi(x_t)$ is linearly decreasing in x_t. Also $v(x_t)$ is continuous in x_t. In addition, it is apparent that the optimization problem in Eq. 1 is recursive until the choice is made to switch to the new technology and, thus, the problem can be represented by the functional[2] equation Eq. 1a.

(1a) $v(x) = \max\{\phi(x),\ E[\Pi_o] + \beta\int v(\xi)dF(\xi)\}$

Figure 1 illustrates Eq. 1a under the assumption that x can taken on values as low as zero and an upper bound, B, above some value x* where $\phi(x^*)=E[\Pi_o]+\beta\int v(\xi)dF(\xi)$. We notice that $E[\Pi_o]+\beta\int v(\xi)dF(\xi)$ does not vary with x and is the expected value of the current period's profit

Figure 1



[2] The functional equation v(x) in Eq. 1a is often used in search models - see, for instance, Telser (1978, pp. 302-307) or Sargent (1987, pp. 57-70).

from the old technology plus the discounted expect value of the next period's optimization problem. That is, $E[\Pi_o]+\beta\int v(\xi)dF(\xi)$ is the value of continuing to use the old technology for at least one more period. Since $\phi(x)$ is linearly decreasing, it can intersect $E[\Pi_o]+\beta\int v(\xi)dF(\xi)$ at only one point. Assuming $\phi(0) > E[\Pi_o]+\beta\int v(\xi)dF(\xi) > 0 > \phi(B)$, there will exist a value of the switching costs, x*, at which the function $\phi(x)$ equals the value of continuing to use the old technology for at least one more period. For current period switching costs, x_t, below x*, the functional v(x) is maximized by chosing to switch forever to the new technology. For current period switching costs, x_t, above x*, v(x) is maximized by continuing to use the old technology for the current period and revisiting the optimization problem again next period. The point x* divides the domain of v(x) into areas of termination and continuation.

We investigate the switching point x* by restating Eq. 1a as follows:

$$(2) \qquad v(x) = \begin{cases} \phi(x) & \text{if } x < x^* \\ \phi(x^*) = E[\Pi_o]+\beta\int v(\xi)dF & \text{if } x \geq x^* \end{cases}$$

From Eq. 2, we can recursively divide the continuation portion of v(x) into termination and continuation regions for period t+1 and associate the probabilities of each event as in Eq 3.

$$(3) \qquad \phi(x^*) = E[\Pi_o] + \beta \int_0^{x^*}\phi(\xi)dF + \beta \int_{x^*}^{B}\phi(x^*)dF$$

Adding and subtracting $\beta\int_0^{x^*}\phi(x^*)dF$ on the right-hand side of Eq. 3 and rearranging terms gives

$$\phi(x^*) - E[\Pi_o]/(1-\beta) = [\beta/(1-\beta)] \int_0^{x^*}[\phi(\xi) - \phi(x^*)]dF$$

or since $\phi(x_t) = \Sigma\beta^{\tau-t}E[\Pi_n]-x_t = E[\Pi_n]/(1-\beta) - x_t$

$$(4) \qquad (E[\Pi_n]-E[\Pi_o])/(1-\beta) - x^* = [\beta/(1-\beta)]\int_0^{x^*}(x^*-\xi)]dF$$

The left-hand side of Eq. 4 can be identified as the difference between the discounted expected future profits from the adoption of the new technology and the discounted expected future profits from remaining with the currently-used technology.

Eq. 4 can be given a useful graphical interpretation. First we define the right hand side of Eq. 4 as the function $\Phi(x)=[\beta/(1-\beta)]\int_0^{x^*}(x^*-\xi)]dF$ and note that $\Phi(x)$ is non-negative and monotonically increasing in x. It is obvious from the definition that $\Phi(0)=0$ Defining the function $\Upsilon(x)=(E[\Pi_n]-E[\Pi_o])/(1-\beta)-x$ as the left hand side of Eq. 4, we see $\Upsilon(x)$ is linearly decreasing in x with slope -1. Assuming the new technology would have a higher expected profit if switching costs are zero[3], $\Upsilon(0)$ will be positive. By continuity there will exist some cost, $\bar{x}$,

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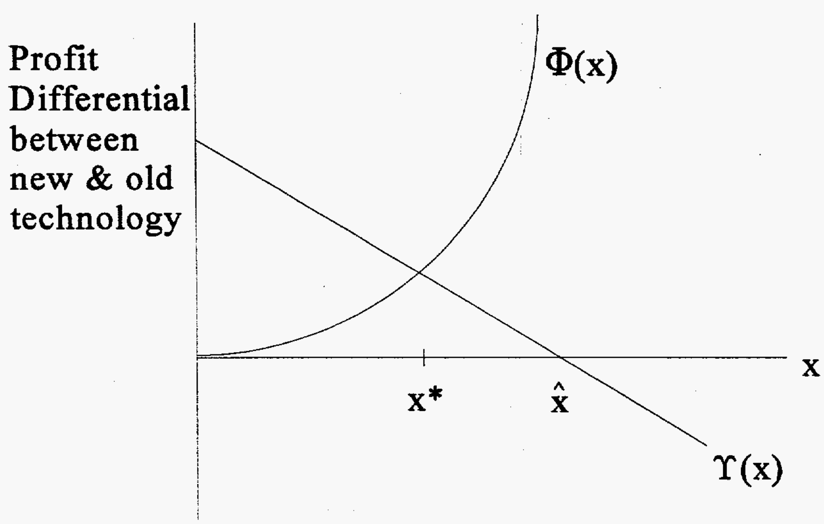
[3] If $E[\Pi_n]\leq E[\Pi_o]$, there would be no interest in switching to the new technology.

beyond which the expected discounted profits from the older technology will be greater than that of the innovation - i.e., $\Upsilon(x)<0$ for all $x>\hat{x}$. Since $\Phi(x)$ increases in x from zero and $\Upsilon(x)$ decreases in x from a positive value to zero, by continuity a value x* will exist where $\Upsilon(x)$ and $\Phi(x)$ are equal. Eq. 4 is this equality. The graphs of the functions $\Upsilon(x)$ and $\Phi(x)$ can be used to determine the value of x*, as shown in Figure 2.

Figure 2



From Eq. 4 we derive Proposition 1.

Proposition 1: With uncertainty in switching costs, a positive profit differential between the new and old technologies can exist under which a profit-maximizing monopolist will continue to use the older technology.

Without uncertainty in the cost of the new technology, the older technology will be continued only if $\sum\beta^{\tau-t}\{E[\Pi_n]-E[\Pi_o]\}\leq 0$. With uncertainly the innovative technology would only be used if the current period's switching costs are less than or equal to $x^*>0$. At x*, the profit differential between the two technologies is $\Upsilon(x^*)$, which is necessarily positive since it equals $\Phi(x^*)>0$. But since $\Upsilon(\hat{x})=0$, $x^*<\hat{x}$, and $\Upsilon'(x)=-1$, the profit differential between the two technologies will be positive between x* and $\hat{x}$ yet the profit-maximizer will not switch from the old technology. QED.

A simple numerical example of the model can be found in a uniform distribution of the adoption costs over the range [2,12]. Let $E[\Pi_n]=18$, $E[\Pi_o]=16$, and $\beta=.9$ in this example. Then $\Upsilon(x)=[(18-16)/(1-.9)]-x=20-x$ and $\Phi(x)=9[(x^2/20)-(x/5)+1/5]$. The value of the switching costs that separates the termination and continuation regions, x^*, is 7.31. That is to say, if the realized value of the cost were any amount less than 7.31 the optimal response would be to terminate the use of the old technology and adopt the innovation. Any larger value for the cost would lead the profit-maximizing, risk neutral monopolist to continue using the old technology.

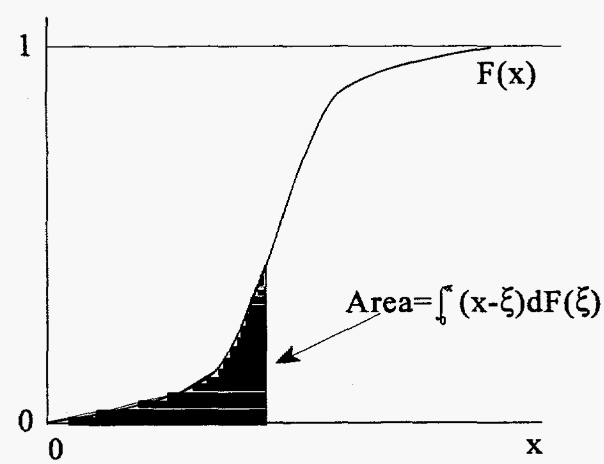
We can also compute the hurdle created in this example by the stochastic switching costs. If there were no uncertainty, the innovation would be adopted as long as the cost is less than 20. This follows because the difference between the discounted expected profit streams of the two technologies is $\Upsilon(x)=20-x$ and $\Upsilon(x)>0$ for all $x<20$. In contrast, for the uniform distribution $x\in[2,12]$ the old technology would only be abandoned if the $x\leq x^*=7.31$. At a cost of 7.31, the difference between the discounted expected profit streams of the two technologies, $\Upsilon(x^*)$, is 12.69. We know that the present value of the expected future profits from the old technology is 160 (=16/1-.9). Therefore, the discounted total profits from the innovative technology, $\phi(x^*)=E[\Pi_o]+\beta\int v(\xi)dF$, needs to be at least 172.69 to stimulate adoption.

The amount $\Phi(x^*)$ is the hurdle that the discounted expected profits of the innovation must exceed beyond mere equality with the discounted expected profits of the current technology in order to stimulate adoption. The hurdle arises because the opportunity cost of waiting for another realization from the stochastic process x can be less than the benefit of waiting. That is

$$(E[\Pi_n]-E[\Pi_o])/(1-\beta) - x = \Upsilon(x) < \Phi(x) \qquad \text{for any } x>x^*.$$

The function $\Upsilon(x)$ readily can be seen as the cost of waiting since the individual gives up this difference in the discounted expected profit streams by passing up the current period realization of the switching costs. We recognize that $\Phi(x)$ is the benefit of waiting by refering to the cumulative probability distribution of Figure 3. By not accepting some $x>x^*$, the individual

Figure 3



maintains the option of discovering a cost lower than x* in any future period. He closes off that option by accepting x. Since $(x - \xi)dF(\xi)$ is the current period surplus resulting from incurring switching costs ξ instead of x multiplied by the probability of realizing ξ, the integral $\int_0^x (x-\xi)dF(\xi)$ gives the cumulative expected current period benefit of being able to pay each cost $\xi \leq x$. The area below the cumulative distribution function and above the abscissa in the range [0,x] is the value of the integral $\int_0^x (x-\xi)dF(\xi)$. Because the option of paying some lower cost $\xi \leq x$ remains open for all future periods starting in the next period if x is not paid in the current period, the cumulative expected benefit of paying a lower cost represents a perpetual annuity beginning in the next period - hence the modifier $\beta/(1-\beta)$ in $\Phi(x)$ When the individual exercises the option by accepting the current realization of x, the option is lost for all future periods and the benefits of lower realizations of the stochastic process are sacrificed.

Knowing the relationship between the cumulative probability distribution function and the function $\Phi(x)$ in Figure 2 enables us to develop an additional proposition on the workings of the model.

Proposition 2: A shift in the distribution of the current period switching costs that decreases the expected value but leaves the distribution otherwise unchanged will increase the innovation's profit hurdle.

To represent a shift in the mean of the state variable's distribution while holding all other aspects of the distribution constant, we will create a new random variable and relate it to the previous variable x. Let us assume that the revealed switching costs, x_t, is a realization of a random variable $X(\omega)$ with ω having a probability space $(\Omega, \mathcal{A}, \mu)$. Furthermore we assume that a new random variable $Z(\omega)$ is defined from $X(\omega)$ by the equation $Z(\omega) = X(\omega)-c$, where $c>0$. Assuming the initial random variable X has a range of $[c,\infty)$, the range of the new random variable will be $[0,\infty)$. Equivalently, one could assume a zero probability for the event $x\in[0,c)$. We represent the cumulative distribution function for X with $F_X(\xi)$ and the cumulative distribution function for Z with $F_Z(\zeta)$. Similarly we define the functions $\Phi_X(x)$ and $\Phi_Z(z)$ for the right hand side of Eq. 4.

Because we have shifted the random variable without otherwise altering the distribution, we immediately recognize that the probability of an event $\zeta\in[0,z]$ for the random variable Z will equal the probability of the event $\xi\in[c,z+c]$ for the random variable X. The relationship between the $\Phi_Z(z)$ and $\Phi_X(x)$ can be seen using the standard transformation of variables technique. We have

$$\Phi_X(x)=\int_0^x[x-\xi]dF_X(\xi)=\int_c^x[x-\xi]dF_X(\xi)=\int_0^{x-c}[x-\zeta-c]dF_Z(\zeta)$$

And since $x-c = z$

$$\int_0^{x-c}[x-c-\zeta]dF_Z(\zeta)=\int_0^z[z-\zeta]dF_Z(\zeta)=\Phi_Z(z)$$

Therefore $\Phi_X(x)=\Phi_Z(x\text{-}c)=\Phi_Z(z)$. That is, shifting the distribution of the switching costs to the left causes a parallel shift in the right hand side of Eq. 4.

Though the right hand side of Eq. 4 shifts with the distribution, the left hand side of Eq. 4 does not shift. The function $\Upsilon(z)$ is identical to $\Upsilon(x)$. As a result, since $\Phi_X(x)<\Phi_Z(x)$, it is evident that if x^* is such that $\Upsilon(x^*)=\Phi_X(x^*)$ then $\Upsilon(x^*)<\Phi_Z(x^*)$. But since $d\Upsilon(x)/dx=-1$ and $d\Phi_Z(x)/dx\geq 0$ the value of x that separates the continuation and termination regions for the random variable X will be greater than the value of z that separates the continuation and termination regions for the random variable Z. That is, for $\Upsilon(z^*)=\Phi_Z(z^*)$, $z^*<x^*$. This implies that

$$\Upsilon(z^*) > \Upsilon(x^*)$$

or that the profit hurdle for Z will be greater than the profit hurdle for X. QED.

It is important to recognize that the profit hurdle for the distribution with the higher expected value is reduced only because the optimal policy for the monopolist is to wait for a realization of switching costs that is lower. This can result from an increase in the benefit of waiting for lower switching costs

Considering again the numerical example of the model, one can illustrate Proposition 2 by assuming the random variable Z has a uniform distribution of the transaction cost over the range [0,10]. Again let $E[\Pi_n]=18$, $E[\Pi_o]=16$, and $\beta=.9$. Then $\Upsilon(z)=20\text{-}z$ and $\Phi_Z(z)=.9(z^2/20)$. The value of the switching costs that separates the termination and continuation regions, z*, is 5.6475. At this value the difference between the discounted expected profit streams of the two technologies, $\Upsilon(z^*)$, is 14.35, and the discounted total profits from the innovative technology, $\phi(z^*)=E[\Pi_o]+\beta\int v(\zeta)dF_Z$, needs to be at least 174.35 to stimulate adoption. The hurdle in the earlier example was a lower amount, 12.69.

In this example, we see that there is an increase in the benefits of waiting. Comparing the solution z* to the solution for the random variable X, it is seen that z* leaves 43.525 percent of the distribution within the continuation region and 56.475 percent in the termination region while x* assigns only 46.89696 percent of the distribution to the continuation region and 53.10304 percent to the termination region. Thus with the decrease in the expected value of the random variable while holding the distribution around the mean unchanged, the termination region has been increased in size.

Finally, one should notice that the benefits of waiting for an additional realization of the switching costs is entirely connected to the future distribution of switching costs. If the monopolist knew that the distribution of switching costs would change from the current period's distribution to a new distribution with a lower expected value (all other aspects constant), then the switching point in the current period would be determined by the future distribution. For instance, suppose that the monopolist knew that some research, training, or discovery would lower uniformly lower the cost of switching for the next and all future periods. This would be as though the current period's distribution of switching costs was drawn from the distribution of the random variable X and all future periods' switching costs would be drawn from the distribution of the random variable Z. The value of the point dividing the continuation and the termination regions would be equal to z* since this is the value equating the two sides of Eq. 4. The likelihood of a current period realization from the distribution of X that is less than z* is, of course, less than the likelihood of a future period realization below z* from the distribution of Z. In the numerical example above, for instance, the chance of getting a switching cost below 5.6475 from a uniform distribution on [2,12] is just 36.475 percent.

This final point which is obvious from Eq. 4 is formalized in the following:

Proposition 3: A shift in the distribution of the next and all future period expected switching costs will increase the current period's profit hurdle.

3. Shared Learning and the Interdependence of Adoption

We can now consider a non-monopoly situation. In this case we will also assume that the learning of one individual will also educate others in the market. The shared learning will be represented by a reduction in the expected switching costs of all participants choosing to adopt the new technology in later periods.

We build on the previous section by continuing to view the adoption of a new technology as switching from one stochastic process to another as in the model of Eq. 1. With more than one potential adopter and shared learning, the optimization problem for the individual becomes a game in which each play can continue to use the old technology or switch to the new technology. The complication that is added is that the benefits of waiting can include receiving a lower expected cost of switching if another player chooses to adopt the technology.

The problem can be set out as a two-person game in which nature makes the first move. Nature, in a sense, selects the current period's cost of switching via the random variable X. Next the two players choose whether to switch now (adopt the new technology in the current period) or wait at least one more period. The two players are assumed to choose at the same time and have identical expected profits and costs. The payoff matrix is given below in Table 1 with Player A's payoff as the first element in each matrix cell and Player B's payoff listed second.

Table 1

		Player B	
		Switch Now	Wait
Player A	Switch Now	$\{E[\Pi_n]/(1-\beta)-x_t, E[\Pi_n]/(1-\beta)-x_t\}$	$\{E[\Pi_n]/(1-\beta)-x_t, E[\Pi_o]+\beta\int v(\zeta)dF_Z\}$
	Wait	$\{E[\Pi_o]+\beta\int v(\zeta)dF_Z, E[\Pi_n]/(1-\beta)-x_t\}$	$\{E[\Pi_o]+\beta\int v(\xi)dF_X, E[\Pi_o]+\beta\int v(\xi)dF_X\}$

Though it may be difficult to see immediately, there will often be a dominant strategy for each player. If Player A waits and Player B adopts, the expected costs of adoption will be lower for Player A in the next period. This is represented by the distribution Z in Player A's payoff in the lower left-hand cell. Since the distribution Z has a lower expected value than distribution X, the payoff to Player A will be greater if Player B switches now than if Player B also waited. That is, $E[\Pi_o]+\beta\int v(\zeta)dF_Z > E[\Pi_o]+\beta\int v(\xi)dF_X$. Similar payoffs exists for Player B. Whenever Nature chooses switching costs such that $E[\Pi_n]/(1-\beta)-x_t < E[\Pi_o]+\beta\int v(\xi)dF_X$, the dominant strategy for each player is to wait. Also there is a dominant strategy in switching now for both players if Nature chooses switching costs in which $E[\Pi_n]/(1-\beta)-x_t > E[\Pi_o]+\beta\int v(\zeta)dF_Z$. For switching costs that place the payoff of switching now between these two values, the Nash equilibrium is a mixed strategy over the two pure strategies.

These results can be easily seen using the numerical examples above. In Table 2, we suppose that Nature has chosen switching costs of 11, the expected value of the distribution X. The value of switching now is therefore 169. Waiting is the obvious dominant stategy for each player. Player A would prefer to wait if Player B chooses to switch now, since he would receive 174.35 rather than 169; and he would prefer to wait if Player B chooses to wait, since he would receive 172.69 by waiting rather than 169. The logic of Player B's optimum choice to wait is similar.

Table 2

		Player B	
		Switch Now	Wait
Player A	Switch Now	{169 , 169}	{169 , 174.35}
	Wait	{174.35 , 169}	{172.69 , 172.69}

A dominant stategy for the two players also exists if Nature chooses switching costs equal to 5. Table 3 illustrates this situation. Player B would prefer to switch now regardless of Player A's choice. By switching now, Player B receives 175 rather than 174.35 if Player A also chooses to switch now. Also Player B receives 175 by switching now rather than 172.69 if Player A chooses to wait. A similar strategy incentive exists for Player A.

Table 3

		Player B	
		Switch Now	Wait
Player A	Switch Now	{175 , 175}	{175 , 174.35}
	Wait	{174.35 , 175}	{172.69 , 172.69}

No dominant strategy exists if Nature chooses switching costs between 5.65 and 7.32. Table 4 shows this situation. If Player A is certain that Player B will choose to wait, Player A's best choice is to switch now since he can receive an expected payoff of 174 rather than an 172.69. However, if Player A is certain that Player B will choose to switch now, the best strategy for Player A is to wait, since by waiting Player A can receive a payoff of 174.35 rather than 174. The strategy incentives are similar for Player B. One solution concept for this game matrix is the mixed strategy Nash equilibrium where each player chooses a probability with which he will play each strategy. The probability with which Player A will chose to wait will increase from zero to one as the costs of switching decreases from 7.32 to 5.65.

Table 4

Player B

		Switch Now	Wait
Player	Switch Now	{174 , 174}	{174 , 174.35}
A	Wait	{174.35 , 174}	{172.69 , 172.69}

The important point the this exercise is to observe that the presence of shared learning pushes the hurdle rate above what it would be if each individual acted and learned independently. This is interdependence acts as a barrier to the adoption of the new technology. This additional hurdle that the profits of the new technology must surmount is all the more important because it comes on top of the hurdle created by individuals independent motivation to wait.

4. Conclusions

This paper has presented a model of technology adoption that may be particularly applicable to community housing developers. The model is based on the existence of sunk costs, the ability of actors to wait before adopting a new technology or technique, and the presence of shared learning. In a market characterized by these factors, one might expect the evolution of some separate organization that would facilitate the joint learning. In other markets such organization have evolved. For instance, the Electric Power Research Institute serves many of the research, developement, and training needs of the electric utility industry. Community housing developers, however, are generally small and numerous organizations. The costs of coordinating the joint actions of such organizations would tend to be extremely costly. As a result the research, development, and training needs of community housing developers are largely left to the public sector.

Bibliography

Arrow, Kenneth J. (1962): "The Economic Implications of Learning by Doing", Review of Economic Studies, 29, June, pp. 155-174.

Dixit, Avinash K., and Robert S. Pindyck (1994): Investment under Uncertainty (Princeton University Press).

Katrakis, J.T., P.A. Knight, and J.D. Cavallo (1994): "Energy-Efficient Rehabilitation of Multifamily Buildings in the Midwest", Argonne National Laboratory Technical Memorandum, ANL/DIS/TM-16, September.

Sargent, Thomas J. (1987): Dynamic Macroeconomic Theory (Harvard University Press).

Telser, Lester G. (1978): Economic Theory and the Core (University of Chicago Press).