TECHNOLOGY CHOICE, PRODUCT LIFE CYCLES, AND FLEXIBLE AUTOMATION

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ABSTRACT

We develop and study a model of technology choice that formalizes the intuition given in the Hayes-Wheelwright Process-Product Life Cycle analysis. We then extend this model to include multiple products with asynchronous life cycles and product-flexible automated technologies. Our results suggest that optimal use of flexible technology can dictate underutilization of the flexibility capability of the technology at some points of the product and process life cycles. Based upon our analysis, we propose a reinterpretation of data collected by Jaikumar.

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1. INTRODUCTION

The concept of the product life cycle, which has been much discussed and debated (e.g., Bass, 1969; Dhalla and Yuspeh, 1976; Wasson, 1978), describes a time-dependent sequence of stages that products go through from the time of initial production and sales to the time of the retirement of the product due to obsolescence. The concept of the process life cycle, introduced by Abernathy and Townsend (1975) and Abernathy and Utterback (1975), describes an analogous sequence of stages that manufacturing processes go through, as the product being manufactered matures. Hayes and Wheelwright (1979a, 1979b) suggest using a two-dimensional map to describe a firm's location in product-process life cycle space. (See Figure 1.) They then develop a theory of technology choice over the product life cycle and discuss the hypothesis that most firms should compete "on the diagonal" of their diagram. That is, as a product evolves from a one-of-a-kind prototype to a high-volume, highly standardized item, the manufacturing process should evolve from a flexible, manual job shop-like process with general purpose tools and broadly skilled workers to a rigid, highly automated, assembly line-like process with special-purpose machines and narrowly trained workers.

In addition, Hayes and Wheelwright (1979b) describe three potentially desirable entrance-exit strategies that may be used over the product life cycle. These are:

A: enter early and get out early, when profit margins first begin to drop;

B: enter early and remain in the market throughout the product life cycle by adapting process technologies as needed; and

C: enter only after the market has matured, and product and process have stabilized to some degree.

Note that strategies A and C may require only one type of process technology, where strategy B is likely to entail a significant technological shift at some point.

The informal theory building of Hayes and Wheelwright has been very useful in helping some analysts and managers develop better intuition concerning strategies for entry, exit, and technology choice over the product life cycle. However, their qualitative mode of analysis limits significantly one's ability to analyze the sensitivity of their descriptions and prescriptions to specific industry circumstances. One purpose of this paper is to build on the Hayes-Wheelwright work by developing a formal model that captures their basic analysis but allows additional exploration and insight into the issues they raise.

Some observers (e.g., Goldhar [1986], Noori [1986]) have suggested that the existence of flexible, automated manufacturing technologies necessitates a reexamination of the Hayes-Wheelwright theory. To wit, manufacturing automation gives rise to the possibility that a firm could use a flexible manufacturing system to simultaneously manufacture several different products, each in a different stage in its life cycle. Under this regime, each product would be manufactured by the system over its entire life cycle; only the mix of products would change as the different products progressed through their life cycles. This line of reasoning suggests that flexible automation decouples the product and process life cycles, because a factory with this technology can economically manufacture a range of products in all stages of their life cycles.

In our model, holding flexible capacity is motivated by the economies of using one technology to manufacture different products whose demand patterns are known but possibly asynchronous. This contrasts with the model of Fine and Freund (1987) where flexible capacity is held as a hedge against uncertainty of the future product demand mix.

The models most closely related to ours are those of Cohen and Halperin (1986) and Hutchinson and Holland (1982). These papers relate, respectively, to sections two and three of our paper. Cohen and Halperin analyze a single-product dynamic, stochastic model of technology choice, where a technology is characterized by three parameters: the purchase cost, the fixed per period operating cost, and the variable, per unit production cost. Their principal result, which is consistent with our analysis of section two, gives conditions sufficient to guarantee that an optimal technology sequence exhibits nonincreasing variable costs.

The Hutchinson and Holland analysis, although quite different from ours in its approach, is quite similar to our section three in spirit. Both pieces of work seek to understand what factors affect the relative profitability of flexible and dedicated technologies in an environment where there are multiple products with different life cycles. Hutchinson and Holland address this question by simulating manufacturing system performance for a stochastic product stream, first assuming all technologies are transfer lines (inflexible), and again, assuming all technologies are flexible manufacturing systems (FMS's). They assume that FMS's have higher variable production costs, but exhibit two types of flexibility: capacity can be added incrementally, rather than all at once, and capacity can be converted to produce more than one product. The authors' 192 simulation runs suggest that the value of flexible systems relative to transfer lines increases in the rate of new product introductions and the maximum capacity of FMS's increase, and decreases in the interest rate and the average volume per part produced.

In section two we formulate a one-product deterministic model of optimal entry, exit, and technology choice over the product life cycle. This model is meant to capture the basic intuition of the Hayes-Wheelwright analysis and permits additional investigation of the issues raised in their work. For this model we solve for the optimal technology choice policies and show how these policies change as a function of certain key parameters. Section three presents a model of technology choice with flexible technologies for two products with overlapping product life cycles. Under the taxonomy of Piore (1986), we focus on technologies for flexible mass production (as was also done in Fine and Freund (1987)) as opposed to technologies for flexible specialization. Our model allows us to address the above-mentioned extension of the Hayes-Wheelwright analysis. One result of this analysis is that optimal deployment of product-flexible manufacturing capacity may dictate devoting flexible capacity to a narrow range of products at the peak of some product life cycles. In Section four we discuss how our results provide insight into the life cycle of a flexible manufacturing system and how they add perspective to the presumption by Jaikumar (1986) that optimal deployment of flexible manufacturing systems will exhibit broad product ranges at all times. Section five contains a discussion of how competition will affect our results and some concluding remarks.

2. THE SINGLE-PRODUCT TECHNOLOGY CHOICE MODEL

We formulate the single product technology choice problem as a discrete-time dynamic program with discount factor δ. Demand for the firm's product is indexed by a_t. To model the time path of demand over the product life cycle, we assume $a_0=0$ and that a_t increases (weakly) monotonically and deterministically to a point τ where it peaks, and then decreases monotonically and deterministically until the market is no longer profitable. We assume that there exists a finite time t^o such that $t^o = \inf \{t: a_t > 0\}$ and a finite time $t^{**} > \tau > t^o$ such that $a_{t^{**}} = 0$ and $a_t \leq 0$ for all $t > t^{**}$.

The firm has two manufacturing processes available to it: a labor-intensive process (indexed by L) that has high variable costs per unit, but a low initial investment and startup cost (I_L); and a capital-intensive process (indexed by K) that has low variable costs per unit, but a high initial investment and startup cost ($I_K > I_L$). We think of the labor-intensive process as being analogous to the job shop process of Hayes and Wheelwright (1979a) and the capital-intensive process as being like their assembly line process. However, in the single-product case of this section, one ought to think of process L as being a labor-intensive assembly or batch flow line, because the product flexibility provided by a job shop is not relevant.

If the firm operates technology T (= L or K) in period t, then it earns period t profits of $\pi(a_t,T)$. (For example, suppose a firm pays a fixed cost per period F_T and a per unit production cost of C_T when it uses technology T, and faces a linear inverse demand curve $p_t(q_t) = a_t-bq_t$, where $p_t(q_t)$ is the market price when q_t is produced; then $\pi(a_t,T) = \max_{q_t} q_t(a_t-bq_t-C_T)-F_T$.) We use ϕ to denote the null technology; that is, the firm is not participating in the market. We assume $\pi(a_t,\phi) = 0$ for all a_t. For T = L or K, we assume that $\pi(a_t,T) \leq 0$ for $a_t \leq 0$ and $\pi(a_t,T)$ is continuous and nondecreasing in a_t for all a_t. We use $\pi_1(a_t,T)$ to denote the first derivative of the profit function with respect to the demand index a_t. Because the capital-intensive process has lower variable costs than the labor-intensive process, we also assume that for $a_t > 0$, $\pi_1(a_t,L) < \pi_1(a_t,K)$, the profit function for the labor-intensive process is less steep than the profit function for the capital-intensive process.

In each period, the firm can either be in the market or out of the market. If not in the market at period t, the firm observes a_t and decides whether or not to enter the market. If it stays out, it earns zero profits ($\pi(a_t,\phi) = 0$). If it chooses to enter, it must first purchase one of the two types of manufacturing technologies (at cost I_L or I_K) before earning operating profits of $\pi(a_t,T)$ for the period. If the firm is already in the market at time t, it may choose to produce with the technology it already owns or purchase the other technology. Disposal costs for either technology are zero. That is, we assume that the net effect of exit costs and salvage value is zero. This assumption is also made by Meyer (1971), Kamien and Schwartz (1972), Hutchinson and Holland (1982), Burstein and Talbi (1985), and others. (We discuss the relaxation of this assumption towards the end of Section Three.) We also assume that a firm cannot maintain a technology that is not being used. That is, after abandoning the use of one technology for another, if the firm ever wants to produce again with the abandoned process, it must pay again the startup/investment cost I_L or I_K.

This problem can be formulated as a dynamic program, as follows. Let T_t be the decision variable that denotes the technology used at time t, so that $T_t \in \{\phi, K, L\}$, where

$$T_t = \begin{cases} \phi & \text{means out of the market;} \\ K & \text{means capital-intensive process;} \\ L & \text{means labor-intensive process.} \end{cases}$$

Also, let $\psi(T_{t-1}, T_t)$ denote the technology switching cost, i.e.,

$$\psi(T_{t-1}, T_t) = \begin{cases} 0 & \text{if } T_{t-1} = T_t \text{ or } T_t = \phi \\ I_K & \text{if } T_{t-1} \neq T_t = K \\ I_L & \text{if } T_{t-1} \neq T_t = L. \end{cases}$$

Then, the technology choice problem can be stated as

$$\max_{\substack{\{T_t\} \\ 1 \le t \le t^{**}}} \sum_{t=1}^{t^{**}} \delta^{t-1} [\pi(a_t, T_t) - \psi(T_{t-1}, T_t)], \qquad (2.1)$$

where $T_0 = T_{t^{**}+1} = \phi$. Note that without loss of generality, we can optimize over an infinite horizon because the firm will optimally choose $T_t = \phi$ for $t > t^{**}$, and periods $t = t^{**}+1, t^{**}+2, \ldots$, will contribute zero to profits. As in Hutchinson and Holland (1982), Fine and Freund (1987), Gaimon (1987), and most of Cohen and Halperin (1986), we assume no interperiod inventories. This is somewhat restrictive, but holds in many circumstances. For example, most service companies are characterized by the fact that services are produced and sold at the same time; their products are not inventoriable. This is also true for perishable-goods producers. In addition, in some style goods industries, e.g., automobiles, producers vary their products each year and choose to manipulate prices and buyer incentives to assure that no interperiod inventories are held.

To analyze this dynamic programming problem, we first define for $T = K$ or L, a_T^0 to be the smallest value of a_t that gives the firm non-negative profits when it owns technology T, i.e., $a_T^0 = \inf \{a : \pi(a,T) \geq 0\}$. We define a^* such that $\pi(a,K) > \pi(a,L)$ if and only if $a > a^*$. (The conditions on $\pi(a,L)$ and $\pi(a,K)$ assure that a^* exists and is unique.)

For the analyses that follow, we assume $a_\tau > \max(a_L^0, a^*)$. This assumption assures that both technologies can be economically viable. Otherwise the problem has only one economically feasible technology, the problem studied in Fine and Li (1986) in a stochastic, duopolistic setting. We define t_* and t^* to be (respectively) the first and last times that $\pi(a,K) > \pi(a,L)$. Therefore $a_{t_*} = a^* = a_{t^*}$ and $t_* < t < t^*$. These times should be thought of as candidate times for switching from the labor-intensive process to the capital intensive process (t_*) and from the capital-intensive process to the labor-intensive process (t^*). As it turns out, these are the optimal switching times only if $\delta = 1$, but they are useful for understanding the analysis of the optimal switching times for the case when $\delta < 1$.

For analogous reasons, we define for T = K,L, t_T and t^T as (respectively) the first and last times that the technology T is profitable. That is, for T = K,L, $t_T = \inf\{t: \pi(a_t,T) \geq 0\}$ and $t^T = \sup\{t: \pi(a_t,T) > 0\}$.

We proceed with the analysis by dividing the parameter space to look at two cases: $a_K^0 \leq a_L^0$ and $a_K^0 > a_L^0$. These cases correspond to whether the capital-intensive process has a lower breakeven point than the labor-intensive process ($a_K^0 \leq a_L^0$) or vice versa. Either of these assumptions may be reasonable, depending on the cost structure associated with the technologies. For example, if the capital-intensive technology requires a large cadre of support labor (maintenance, engineers, etc.) to keep it running, then it will require high levels of output to cover the fixed costs of keeping the plant operating, so $a_K^0 > a_L^0$ would be reasonable. On the other hand, if the highly automated plant can be kept up and running with a small staff, then, because of its low variable costs, the capital-intensive technology may have a lower breakeven point than the labor-intensive one.

In the former case (Figure 2) we have $a^* \le a_K^0 \le a_L^0 < a_\tau$. In this case, the firm will never switch technologies. To see this, first note that $\pi(a,K) > \pi(a,L)$ for all values of a that yield positive profits with either technology. If the firm invests in technology K, then it will never switch to technology L because $\pi(a,K) > \pi(a,L)$ over the entire range where technology L yields positive profits. On the other hand, if the firm invests in the labor-intensive technology (because its investment cost is significantly lower), it will be because the capital-intensive technology was too costly to invest in at all. Thus, there are only three strategies a firm would follow in this case: invest only in the capital-intensive process, invest only in the labor-intensive process, or stay out of the market.

To determine which of these policies is optimal, we first let $\pi(a_t,T)^+ = \max(\pi(a_t,T), 0)$ and let $U_T(s)$ denote the discounted profit stream to the firm if it invests in technology T (= K or L) at time $s \epsilon (t_T, t^T)$ and uses it until time t^T. (Our assumption of a zero net effect on profits of exit costs and salvage benefits guarantees that t^T is the optimal exit time.) Therefore, we have

$$U_T(s) = \sum_{t=0}^{\infty} \delta^t \pi(a_{s+t},T)^+.$$

If the firm invests in technology T at time s, its profit net of investment (calculated at time s) is $U_T(s) - I_T$. Consider postponing the investment one period from time s to time s + 1. The benefit of this postponement is $\delta[U_T(s+1) - I_T] - [U_T(s) - I_T]$, so that the firm will find it beneficial to postpone the investment in technology T from s to s+1 if $(1-\delta)\ I_T > \pi(a_s,T)^+$. This observation yields three conclusions, stated as

Proposition 1. Assume technology T is the only technology available. If $(1-\delta)I_T \geq \pi(a_\tau,T)$, then the firm will never enter with technology T. If $(1-\delta)I_T < \pi(a_\tau,T)$, then S_T, defined as the smallest integer that satisfies $t_T \leq S_T \leq \tau$ and $\pi(a_{S_{T-1}},T) \leq (1-\delta)I_T \leq \pi(a_{S_T},T)$, is the candidate entry time for technology T. If $U_T(S_T)-I_T < 0$, then the firm will never use technology T and we set $S_T = \infty$; otherwise the firm will enter at time $S_T < \infty$.

Proposition 1 suggests a two-stage calculation for the determination of the optimal entry time when only one technology, technology T, is to be considered. First the entry time (S_T) that maximizes the present value of profits net of investment is calculated. The identified time is the optimal entry time if discounted profits from entry at that time are positive. That is, if $U_T(S_T)-I_T > 0$.

Note that if $\delta < 1$ then S_T will always be larger than t_T and if $\delta=1$ then $S_T = t_T$. That is, with a positive interest rate the optimal time to invest will always be no earlier than the first time that the technology generates a positive profit. The investment decision is postponed beyond t_T because the firm must earn a strictly positive profit from the technology before foregoing the opportunity cost of the capital it must invest for the acquisition.

To find the optimal policy for the case $a_K^0 \leq a_L^0$, we first calculate S_K, S_L, $U_K(S_K)-I_K$, and $U_L(S_L)-I_L$. If $U_K(S_K)-I_K$ and $U_L(S_L)-I_L$

are both negative, then the firm will never enter. If only one of these terms is positive, then the firm will enter with the corresponding technology at the candidate entry time for that technology and exit at the corresponding t^T. If both are positive, the firm will enter at S_K with technology K and exit at t^K if $U_K(S_K)-I_K > \delta^{S_L-S_K}U_L(S_L)-I_L$ and will enter at S_L with technology L and exit at t^L if this inequality is reversed.

In the second case, where $a_L^0 < a_K^0 < a^* < a_\tau$ (Figure 3), there are six possible optimal technology strategies, depending on the parameters of the model. These are: (1) use only the labor-intensive technology, over the entire course of the product life cycle; (2) use only the capital-intensive technology; (3) enter with the labor-intensive technology and switch to the capital-intensive technology when demand becomes sufficiently large; (4) enter with the capital-intensive technology and switch to the labor-intensive process in the twilight of the product's life cycle; (5) enter with the labor-intensive process, switch to the capital-intensive process when demand is high, and then switch back to the labor-intensive process toward the end of the life cycle; and (6) do not enter the market. We will sometimes denote these stragetiges, respectively, by the following shorthand notation: L, K, L-K, K-L, L-K-L, and ϕ. Our usage of this shorthand will be clear from the context. The analysis below identifies the parameter conditions that support each of these six strategies.

To begin the analysis, we first note that since we assume that the net effect on profits of exit costs and salvage benefits is zero, deriving optimal exit times is straightforward: If the firm holds technology L at t* or later, then it will never switch to K after that point (because $\pi(a_t,L) > \pi(a_t,K)$ for all $t > t^*$) and it will exit at time t^L. If the firm holds technology K at t*, then it may choose to switch to technology L some time after t*, but if it does not switch, it will exit at t^K.

The next results characterize the optimal times to switch technologies - either from the capital-intensive to the labor-intensive or vice versa. Since we assume that the net effect of exit costs and salvage benefits from abandoning a technology is zero, the tradeoff involves comparing the investment cost of purchasing the new technology with the relative differences in discounted cash flows from the different technologies. As in the preceding analyses, the optimal switching times are adjusted from t_* and t^* to reflect the requirement that the differential profits from the new technology exceed the opportunity cost of the money to be invested.

Suppose the firm is already operating the capital-intensive technology at time s and is considering a switch to the labor-intensive process. If the firm switches at time s (and never switches back) then the profits from s onward will be

$$\sum_{t=0}^{\infty} \delta^t \pi(a_{s+t}, L)^+ - I_L,$$

whereas if it switches at time s+1, profits will be

$$\pi(a_s,K)^+ + \sum_{t=1}^{\infty} \delta^t \pi(a_{s+t},L)^+ - \delta I_L.$$

The benefit to postponement from time s to time s+1 of the switch from K to L is the difference:

$$B_{KL}(s) = \pi(a_s,K)^+ - \pi(a_s,L)^+ + (1-\delta)I_L.$$

The graph of this function is shown in Figure 4. Since $\pi(a_s,K)^+ = 0$ for $a_s \leq a_K^0$ and $\pi_1(a_s,K) > \pi_1(a_s,L)$, $B_{KL}(s)$ is minimized at t_K and t^K, where $a_t = a_K^0$. This observation leads to the conclusion that if $B_{KL}(t_K) = \pi(a_K^0,K) - \pi(a_K^0,L) + (1-\delta)I_L \geq 0$, then the firm will never switch from K to L.

From Figure 4, we observe that $B_{KL}(t) < 0$ can occur in two regions: one in the interior of $(t_L, t*)$ and the other in the interior of $(t*, tL)$. Clearly, the firm would never switch from K to L in the first of these, since it would not have even acquired technology K prior to $S_K \geq t_K$. On the other hand, in the latter region, as demand is declining, the firm might find it profitable to switch back to the labor-intensive technology, with its lower breakeven point. We denote by S_{KL} the candidate time for switching from process K to process L.

<u>Proposition 2</u>. If $B_{KL}(t^K) \geq 0$ then the firm will never switch from the capital-intensive technology to the labor-intensive technology. If $B_{KL}(t^K) < 0$, then S_{KL}, defined by $t^* < S_{KL} \leq t^K$ and $B_{KL}(S_{KL}-1) > 0 \geq B_{KL}(S_{KL})$, is the candidate time to switch from the capital-intensive technology to the labor-intensive technology.

Similarly, to analyze a potential switch from the labor-intensive to the capital-intensive process, we can define the benefit from postponing such a switch from time s to time s+1, by

$$B_{LK}(s) = \pi(a_s,L)^+ - \pi(a_s,K)^+ + (1-\delta)I_K.$$

Note that $B_{LK}(s)$ is minimized at $s=\tau$ (Figure 5).

Proposition 3. If $B_{LK}(\tau) \geq 0$, then the firm will never switch from L to K. If $B_{LK}(\tau) < 0$, then there exists a unique S_{LK}, satisfying $t* \leq S_{LK} \leq \tau$ and $B_{LK}(S_{LK}-1) > 0 > B_{LK}(S_{LK})$, which is the candidate switching time.

Together, the three propositions on the candidate adoption times (S_L, S_K) and candidate switching times (S_{KL}, S_{LK}) yield the following characterization (illustrated with a decision tree in Figure 6) of the technology-choice dynamic program stated in (2.1):

Theorem 1. There are six possible optimal technology policies for this model. These policies are:

1. Never enter the market ($T_t = \phi$ for all $t \geq 0$). This policy is optimal whenever

$$U_L(S_L) < I_L, \text{ and}$$
$$U_K(S_K) < I_K.$$

2. Only use the labor-intensive technology ($T_t = L$ for $S_L \leq t \leq t^L$, $T_t = \phi$ otherwise). This policy is optimal whenever

$$U_L(S_L)-I_L > \max(0, \delta^{S_K-S_L}(U_K(S_K)-I_K) + \max(0, \delta^{S_{KL}-S_K}(U_L(S_{KL})-U_K(S_{KL})-I_L)), \text{ and}$$

$$U_L(S_{LK}) > U_K(S_{LK})-I_K + \max(0, \delta^{S_{KL}-S_{LK}}(-U_K(S_{KL}) + U_L(S_{KL})-I_L)).$$

3. Only use the capital-intensive technology ($T_t = K$ for $S_K \leq t \leq t^K$, $T_t = \phi$ otherwise). This policy is optimal whenever

$$U_K(S_K)-I_K > \max(0, \delta^{S_L-S_K}(U_L(S_L)-I_L) + \max(0, \delta^{S_{LK}-S_K}(U_K(S_{LK})- U_L(S_{LK})-I_K)), \text{ and}$$

$U_K(S_{KL}) > U_L(S_{KL})-I_L$.

4. Enter the market with the labor-intensive technology and later switch to the capital-intensive technology ($T_t = L$ for $S_L \leq t < S_{LK}$, $T_t = K$ for $S_{LK} \leq t \leq t^K$, and $T_t = \phi$ otherwise). This policy is optimal whenever

$U_L(S_L)-I_L + \delta^{S_{LK}-S_L} (U_K(S_{LK})-U_L(S_{LK})-I_K) > \max (0, \delta^{S_K-S_L} (U_K(S_K)-I_K))$,

$U_L(S_{LK}) < U_K(S_{LK})-I_K$, and

$U_L(S_{KL})-I_L < U_K(S_{KL})$.

5. Enter the market with the capital-intensive technology and later switch to the labor-intensive technology ($T_t = K$ for $S_K \leq t < S_{KL}$, $T_t = L$ for $S_{KL} \leq t \leq t^L$, and $T_t = \phi$ otherwise). This policy is optimal whenever

$U_K(S_K)-I_K > \max (0, \delta^{S_L-S_K} (U_L(S_L)-I_L)) + \delta^{S_{LK}-S_K} \max (0, U_K(S_{LK})-$
$U_L(S_{LK})-I_K))$, and

$U_L(S_{KL})-I_L > U_K(S_{KL})$.

6. Enter with technology L, switch to technology K in the high-demand part of the life cycle, then switch back to technology L in the decline phase of the life cycle ($T_t = L$ for $S_L \leq t < S_{LK}$ and $S_{KL} \leq t \leq t^L$, $T_t = K$ for $S_{LK} \leq t \leq S_{KL}$, and $T_t = \phi$ otherwise). This policy is optimal whenever

$U_L(S_L)-I_L + \delta^{S_{LK}-S_L} (U_K(S_{LK})-U_L(S_{LK})-I_K > \max (0, \delta^{S_K-S_L} (U_K(S_K)-I_K))$,

$U_L(S_{KL})-I_L > U_K(S_{KL})$, and

$U_K(S_{LK})-I_K + \delta^{S_{KL}-S_{LK}} (-U_K(S_{KL}) + U_L(S_{KL})-I_L) > U_L(S_{LK})$.

Figure 7, which is divided into six regions, illustrates how the startup/investment costs, I_L and I_K, determine which of the six policies is optimal. The region labels are abbreviations for the policies that are optimal in those regions. For example, L-K-L means use technology L from time S_L to S_{LK}, use K from S_{LK} to S_{KL} and use L from S_{KL} to t^L. The graph illustrates that the six policies are mutually exclusive and collectively exhaustive. (Note that since $I_K > I_L$ by assumption, we are only concerned with the area of the graph below the 45^o line.) For I_K and I_L sufficiently large (region ϕ in the figure), the optimal policy is to stay out of the market completely. This region consists of (I_L, I_K) pairs such that $U_L(S_L) - I_L < 0$ and $U_K(S_K) - I_K < 0$, as in Theorem 1. The other regions are defined analogously, following the characterization in Theorem 1.

We can contrast this analysis with the Hayes-Wheelwright proposition that firms stay on the diagonal of the product-process life cycle matrix. Presumably the diagonal of their matrix corresponds to the L-K strategy. That is, enter with the labor-intensive technology and then switch permanently to the capital-intensive technology when industry demand has grown sufficiently. Clearly, our model admits a wider range of potentially optimal strategies than this.

Observe that strategy B of Hayes-Wheelwright, enter early and stay throughout the product life cycle, corresponds to our strategy L-K (or perhaps L-K-L), and their strategy C, enter late in the growth stages or early in the maturity stage, corresponds to our strategy K. However, our model never uses entry-exit strategy A of Hayes-Wheelwright which dictates early entry and early exit in a product market. Strategy A would be more reasonable in a multiproduct, multifirm world. A firm could specialize in supplying product markets early in their life cycles. For each product, the firm would enter early, but then depart to supply the next new product once the competition in the old product became severe. We discuss multiproduct models in sections 3 and 4 and competition in section 5.

The contrasts between the Hayes-Wheelwright analysis and ours suggest several lines of inquiry, both empirical and theoretical. On the empirical side, one might try to estimate the parameter values for our model in a number of industries and see whether industries that exhibit parameters that yield optimality of, for example, the L-K (stay on the diagonal) strategy, exhibit behavior consistent with the model's predictions. On the theoretical side, we could extend the model in several ways, to increase realism. In the two sections, we extend our model to include multiple products and focus our analysis on asynchronous product life cycles. One could also extend the model to include multiple-firm competitive interaction. We discuss this subject in Section 5.

3. THE TWO-PRODUCT TECHNOLOGY CHOICE MODEL

There are a number of issues that arise in the manufacturing technology choice problem for a multiproduct firm that cannot be captured by the single-product model of the previous section. For example, if a firm chooses to produce several products with asynchronous life cycles, then it may employ strategy A of Hayes and Wheelwright, commencing manufacture of the first product early in its life cycle and dropping that product during the maturity phase, while switching to the next product early in its life cycle, etc. In addition, the study of multiple products permits explicit consideration of the use of product-flexible manufacturing technologies.

For ease of analysis and exposition, we limit ourselves in this section to studying a two-product or two-product-family model. Most of the important intuition can be illustrated with this case. We label the two products (or product families) by A and B, respectively. We assume there are three types of technologies: a labor-intensive, job shop technology (indexed by L) that can produce both products; a capital-intensive, dedicated technology (indexed by K_A or K_B) that can produce only one product; and a capital-intensive, flexible (automated) technology (indexed by K_{AB}) that can produce both products. As in the previous section, we assume that the labor intensive technology has a low investment and startup cost and a high variable cost per unit produced, relative to the capital-intensive technologies. Extending in the obvious way the notation for investment costs used in the previous section, we assume $I_L < I_{K_A} < I_{K_{AB}}$, $I_L < I_{K_B} < I_{K_{AB}}$, and $I_{K_{AB}} < I_{K_A} + I_{K_B}$. The inequalities for the capital-intensive technology investment costs parallel the assumptions in Fine and Freund (1987), that the flexible automated technology is more costly to acquire and install than either of the nonflexible technologies (otherwise one or both of the nonflexible technologies would be economically dominated by the flexible automated technology) and that acquiring and installing the flexible automated technology is less costly than acquiring and installing both nonflexible capital-intensive technologies (otherwise the flexible automated technology is dominated by the joint acquisition of the two nonflexible technologies).

We let a_t and b_t, respectively, be the demand indices for products A and B. Then $\pi^A(a_t, T_t^A)$ and $\pi^B(b_t, T_t^B)$ represent the period t profits from products A and B, respectively, given that the firm uses technology T_t^A for producing product A and T_t^B for product B. Extending the notation of the previous section, we also define $t_A^o = \inf\{t: a_t > 0\}$ and $t_B^o = \inf\{t: b_t > 0\}$. As in the previous section we assume that the firm earns zero profits from markets in which it is not a participant. That is, $\pi^A(a_t, \phi) = \pi^B(b_t, \phi) = 0$ for all values of a_t and b_t. We also assume that for all a_t and b_t, $\pi^A(a_t, K_A) = \pi^A(a_t, K_{AB})$ and $\pi^B(b_t, K_B) = \pi^B(b_t, K_{AB})$. That is, operating profits from a given market are the same for each type of capital-intensive technology. (This assumption allows us to simply use K to represent K_A or KAB as the argument of the profit functions.) This assumption -- of no economies of scope in operating profits -- is justified on the grounds that, for highly automated, capital-intensive technologies, the variable operating costs, which are essentially the materials costs plus a small amount of labor costs, will not depend significantly on whether the capital-intensive technology is dedicated or flexible. We discuss the relaxation of this assumption later.

We do assume that the operating cost structure of the labor-intensive technology differs from that of the capital-intensive technologies. As in the previous section, we model these differences through assumptions on the first derivative of the profit function with respect to the demand index. In particular, we assume $\pi_1^A(a_t, L) < \pi_1^A(a_t, K)$ for $a_t > 0$ and $\pi_1^B(b_t, L) < \pi_1^B(b_t, K)$ for $b_t > 0$. Also, the profit functions are negative for negative levels of the demand index and nondecreasing in the respective demand indices. As in the previous section, we assume that the net effect of exit costs and salvage value for each technology is zero and that a firm cannot maintain a technology that is not being used.

With respect to the life cycles of the two products, we assume that each product has a life cycle path that satisfies the assumptions of the previous section. We examine two cases: synchronous life cycles and asynchronous life cycles. (See Figures 8a and 8b respectively.) The former case occurs when the life cycle stages of the two products coincide roughly in time. Formally, we say that products A and B have synchronous life cycles if for T = L or K_{AB}, $\pi A(a_t,T) + \pi B(b_t,T)$ is quasiconcave in t. That is, $\pi^A(a_t,T) + \pi B(a_t,T)$ is unimodal in t.

We let τ_A and τ_B represent the times when a_t and b_t, respectively, reach their peaks. For T = L, K_A, K_B, and K_{AB}, in the manner of Proposition 1 in the previous section, we define S_T to be the candidate entry time for each technology. Without loss of generality, we assume $S_{K_A} \leq S_{K_B}$, that is, product A precedes product B. We define the product life cycles of products A and B to be asynchronous when inf {t: b_t > 0} > τ_A, i.e., when product B's life cycle does not start until after product A's life cycle has peaked. By our definitions, synchronicity and asynchronicity of life cycles are not collectively exhaustive, but these definitions are useful for analyzing the qualitative properties we wish to study.

In calculating $S_{K_{AB}}$ and $U_{K_{AB}}(S_{K_{AB}})$ in the asynchronous life cycles case (figure 8b), the firm earns profits from product family A right up until time t_A^{**} and earns profits from product family B beginning at t_B^o. In contrast, when both K_A and K_B are used, operating profits from product family A will cease at exit time t^{K_A} and operating profits from product family B will not begin until entry time S_{K_B}. Thus, when flexible automation is acquired, its optimal use can generate more total operating profits than using separate, dedicated, automated processes for each product. (This will also depend on the magnitude of the difference between $S_{K_{AB}}$ and S_{K_A}, the times when operating profits begin to flow from product family A under the two respective strategies.) When a longer sequence of products is considered (figure 9), this advantage of the flexible technology becomes even more pronounced: firms can be more aggressive in both their entry and exit times because all the fixed costs do not have to be carried by one product; products very early or late in their life cycles can "free ride" or at least share-the-ride with other products.

Given this formulation of technology types and product life cycles, we wish to explore what types of technology investment policies are optimal in certain situations. To focus on insights related to the existence of the flexible, capital-intensive technology, we limit our analysis primarily to two simplified cases: (1) only the L and K_{AB} technologies are available, (2) only the K_A, K_B, and K_{AB} technologies are available. The formal analysis that supports the results of this section is virtually identical to that of section 2, so we suppress formal arguments in what follows and rely on the readers' understanding of the previous section.

We first examine case (1), where only the labor-intensive flexible technology (L) and capital-intensive flexible technology (K_{AB}) are available. In the synchronous life cycle case, the analysis parallels that of Section 2 exactly. Because each technology can manufacture both products, we need only be concerned with the two-product profit function, $\pi^{AB}(a_t,b_t,T) \equiv \pi^{A}(a_t,T) + \pi^{B}(b_t,T)$, for T = L or K_{AB}. Let $\tau_{AB}(T)$ be the smallest time at which $\pi^{AB}(a_t,b_t,T)$ achieves its maximum. (The time $\tau_{AB}(T)$ is unique if $\pi^{AB}(a_t,b_t)$ is strictly quasiconcave in t.) As in Section 2, we can define the breakeven times $t_T = \inf\{t: \pi^{AB}(a_t,b_t) \geq 0\}$ and $t^T = \sup\{t: \pi^{AB}(a_t,b_t) \geq 0\}$ for T = L, K_{AB}. As in the previous section, in the case where the capital-intensive technology has the lower breakeven time, i.e., $t_{K_{AB}} \leq t_L$, the firm will never switch technologies, so there are only three possible optimal strategies: never enter, use technology L from s_L to t^L, or use technology K_{AB} from $s_{K_{AB}}$ to $t^{K_{AB}}$. If, on the other hand, the labor-intensive technology has the earlier breakeven time, i.e., $t_L < t_{K_{AB}}$, then there are six possible strategies, analogous to those in Theorem 1, which we denote by ϕ, L, K_{AB}, L-K_{AB}, K_{AB}-L, and L-K_{AB}-L, extending the notation of Section 2 in the obvious way.

For the asynchronous life cycles case, there are four additional strategies that may be optimal. Each of these involves using the flexible automated technology during the mature stage of product A, switching to the labor-intensive technology for a period of time while product A demand declines and product B demand is early in its growth stage, and then switching back to K_{AB} during the high-demand period of product B's life cycle. We denote the four strategies that have this characteristic by $L\text{-}K_{AB}\text{-}L\text{-}K_{AB}$, $K_{AB}\text{-}L\text{-}K_{AB}\text{-}L$, $L\text{-}K_{AB}\text{-}L\text{-}K_{AB}\text{-}L$, $K_{AB}\text{-}L\text{-}K_{AB}$, depending, respectively, upon whether technology L is used early in product A's life cycle, late in product B's life cycle, in both these periods, or in neither.

One effect of the existence of the flexible, capital-intensive technology, relative to a situation where only dedicated, capital-intensive technologies exist as an alternative to the labor-intensive job shop, is that the technology acquisition problem is easier to analyze. For example, in the two-product, synchronous-life-cycle technology choice problem, where the available technologies are L, K_A, and K_B, the analysis is quite complex. One source of complexity in this regime is that two different technologies may be used at the same time, one for each product: whereas for the problem above, at any given point in time, both products are produced either with the flexible labor-intensive or the flexible capital-intensive technology. For this three-technology, two-product problem, there are fourteen different technology acquisition timing sequences that can be optimal, compared with only six possible strategies for the case analyzed above. Using the shorthand notation developed above, these fourteen are: ϕ, L, K_A, K_B, $K_A\text{-}K_B$, $L\text{-}K_A\text{-}K_B$, $K_A\text{-}K_B\text{-}L$, $L\text{-}K_A\text{-}K_B\text{-}L$, $L\text{-}K_A$, $L\text{-}K_B$, $K_A\text{-}L$, $K_B\text{-}L$, $L\text{-}K_A\text{-}L$, and $L\text{-}K_B\text{-}L$.

We next examine case (2), where only the nonflexible capital-intensive (K_A, K_B) and flexible capital-intensive (KAB) technologies are available. Several observations about this case are of interest. First, it can never be optimal to switch from K_{AB} to either K_A or K_B. This result arises because of our assumptions that the technologies do not have capacity constraints and that both (flexible and nonflexible) capital-intensive technologies yield the same profit streams in each market. If capacity constraints were imposed, optimal policies could involve a portfolio of flexible and nonflexible automated technologies, as is the case in Fine and Freund (1987).

A second observation is that if the firm acquired technology K_A to enter market A, then it will never switch from technology K_A to K_{AB} when it is ready to enter market B. This result arises from the assumption that technology K_A has zero net salvage value plus exit cost, and the assumption that $I_{K_{AB}} > I_{K_B}$. Once the K_A technology has already been purchased, the least expensive way to enter the market B is with K_B.

A third observation relates to the discount factor, δ. When δ is large (i.e., close to one), the optimal policy may specify purchase of K_{AB} for use over both product life cycles, whereas a smaller value of δ (with all other parameters unchanged) may dictate purchase of K_A for product A and then K_B after product B's life cycle has begun. A higher interest rate (smaller δ) discourages investment in the flexible capacity because it requires the entire outlay up front. Sequential investment in the dedicated technologies avoids acquiring any capabilities before they are needed. If different companies use different hurdle rates for technology investments, those with the higher rates will find the flexible capacity less attractive.

Whether the life cycles are synchronous or asynchronous, the above observations imply that there are only five technology policies that can be optimal. These are: never enter either market (ϕ), use K_A in market A and K_B in market B (K_A-K_B), use K_A in market A and do not enter market B (K_A), use K_B in market B and do not enter market A (K_B), and use K_{AB} for both markets (K_{AB}). For a given set of parameter values, one can solve explicitly for the optimal technology policy, as follows: For $T = K_A$, K_B, K_{AB}, calculate the candidate entry times S_T, the exit times t_T, and the discounted cash flows $U_T(S_T)-I_T$, as was done in the previous section. (Note that $U_{K_{AB}}(S_{K_{AB}})$ includes profits for two markets.) If $U_T(S_T)-I_T \leq 0$ for $T = K_A$, K_B, and K_{AB}, then the optimal policy is to never enter either market. If only one of these say T', is positive, then it is optimal to enter at $S_{T'}$ with technology T' and remain in the corresponding market(s) until $t^{T'}$. If $U_T(S_T)-I_T$ is positive for $T = K_A$ and for $T = K_B$, but negative for $T = K_{AB}$, then the optimal policy is, for $T = K_A$ and K_B: enter with technology T at S_T and exit at t^T, from the respective markets.

The other possibilities all have $U_T(S_T)-I_T > 0$ for $T = K_{AB}$ and one or both of $T = K_A$ or $T = K_B$. If both of the latter are positive, then the firm should use the K_{AB} only policy if $U_{K_{AB}}(S_{K_{AB}})-I_{K_{AB}} \geq U_{K_A}(S_{K_A}) - I_{K_A} + U_{K_B}(S_{K_B}) - I_{K_B}$ and use the K_A-K_B strategy otherwise. If $U_T(S_T) - I_T > 0$ for only one of $T = K_A$ or K_B, then the firm should use K_{AB} only policy if it gives higher net profits, and the K_A-only or K_B-only strategy otherwise.

One interesting outcome of this model is that a firm will never acquire the flexible technology after already owning a dedicated technology. This result, which suggests the adage, "once an inflexible mass producer, always an inflexible mass producer," provides an interesting juxtaposition with the numerous exhortations by the promoters of flexible manufacturing systems that firms should abandon their inflexible, mass production technologies in favor of flexible, automated technologies.

There are (at least) three ways that we could extend our model to reverse the result that an inflexible mass producer should never invest in flexible automation. First, we could assume that technology K_A has a positive net salvage value minus exit costs, denoted by S(A). If S(A) is sufficiently large, that is, if the net cost (after selling K_A) of purchasing K_{AB} to produce products A and B is less than the cost of adding K_B to produce product B, then we could obtain the result that the firm switches from inflexible mass production to flexible automation. (The exact conditions for this move to be optimal depend on the salvage values of the other two technologies as a function of time and on the optimal entry and exit times.)

Although an assumption of positive net salvage values can achieve the result that firms switch to flexible automation, we think it does so for the wrong reasons. We are not aware of any advocates of flexible automation who promote the technology based on the cash flow benefits of selling the equipment it replaces. Rather, flexible automation is touted for operational efficiencies; superior manufacturing performance in cost, delivery, and flexibility; and a wide range of strategic benefits.

A second extension of our model, one to include operational efficiences of flexible automation, i.e., economies of scope in operation, could also be constructed to reverse the result that inflexible mass producers should not switch over to flexible automation. Suppose the operating costs of producing product families A and B on the flexible technology were assumed to be lower than the operating costs of producing both families on the two inflexible technologies. In that case, the operating profits from the two-types of technologies would satisfy

$$\pi^{AB}(a_t, b_t, K_{AB}) > \pi^{A}(a_t, K_A) + \pi^{B}(b_t, K_B). \qquad (*)$$

Then, provided that the difference between these two quantities is sufficiently large, the optimal technology policy could involve switching from the inflexible technology to flexible automation.

The question of when (if ever) inequality (*) actually holds in practice is one that urgently needs further research. Theoretically, using the single flexible technology rather than two inflexible technologies could eliminate some duplication line and/or overhead functions and provide some economies of scope. However, the added complexity of the system may decrease manufacturing focus and increase coordination costs. We know of no empirical work that has addressed these issues.

A third extension of our model, one that admits a larger sequence of different product families and uncertainty in the technology investment costs, could also reverse the result that an inflexible mass producer never switches to flexible automation. Consider a sequence of product families, 1, 2,...,n, that have overlapping product life cycles as in Figure 9. Suppose there is a flexible, capital-intensive technology, denoted by K_F that can produce all of these product families and there are n dedicated, nonflexible technologies $K_1, K_2, \ldots, K_n$, each of which can manufacture only one product family. For $j = 1, 2, \ldots, n$, let I_{K_j} denote the investment/startup cost associated with acquiring dedicated technology K_j. Let $I_{K_F}(t)$ denote the (stochastic) cost of acquiring the flexible capacity. We assume that the flexible capacity is subject to stochastic technological innovation that can decrease the effective cost of acquiring it. Then, if $I_{K_F}(0)$ is high, the firm may acquire K_1 and perhaps K_2 and K_3, for the early products. If, for some t, $I_{K_F}(t)$ has declined sufficiently, then it will be optimal for the firm to switch to the flexible technology, and use it thereafter. Thus, a richer model with multiple products and a nonstationary investment cost can yield a result such that a mass producer converts to a flexible technology.

4. THE LIFE CYCLE OF A FLEXIBLE MANUFACTURING SYSTEM

Of particular interest to us is the asynchronous life cycles case when the optimal strategy is to only purchase the flexible capacity and use it for all of the product families. In the two product case (Figure 8b), this strategy requires acquiring the flexible K_{AB} technology at $S_{K_{AB}}$ for the mature and late stages of product-family A's life cycle and continuing its use until $t^{K_{AB}}$, through most of product-family B's life-cycle. A property of the optimal policy is that during the time period $[S_{K_{AB}}, t_B^o)$ the product-flexible technology is used only to manufacture product-family A; during the period (t_B^o, t_A^{**}) the flexible capacity is used to manufacture both product families; and during the period $(t_A^{**}, t^{K_{AB}})$ the flexible capacity only works on product-family B.

This characteristic of the optimal policy lends an interesting perspective to Jaikumar's (1986) observation that, for the data he collected, a typical flexible manufacturing system (FMS) in the U.S. manfuactures significantly fewer machined parts than a typical FMS in Japan. Jaikumar suggests that this observation lends credence to a conclusion that FMS managers in the U.S. are less competent than their Japanese counterparts. Because this conclusion is based on numerous other points, we are not in a position, in this paper, to either discuss it further or to dispute it. However, we do wish to illustrate how our model may help to illuminate the discussion.

Jaikumar's data, although it was collected over a period of several years, essentially represents a snapshot in time of FMS usage in the U.S. and Japan. He makes no claims to having attempted to develop a time series of observations. If the Japanese began investing in FMS technology in earnest earlier than their U.S. competitors (a premise consistent with Jaikumar's report that the Japanese outspent the U.S. in FMS by a factor of two from 1982 to 1987) then they may have progressed further along the life cycle of the FMS technology as compared with their U.S. competitors. Therefore, a snapshot in time of FMS development in the U.S. and Japan could capture the FMS's in two countries in different stages of their life cycles.

Figure 8b, considered in the light of our characterization of the K_{AB}-only technology policy, is suggestive of the product pattern produced over the life cycle of a flexible manufacturing system for the two-product case. Figure 9 is suggestive of the n-product case. In either case, early in the FMS's life cycle, while the production team is learning how to use the technology, few products (perhaps all from one product family) may be manufactured on the FMS. This stage in the FMS life cycle corresponds to the period $(S_{K_{AB}}, t_B^o)$ in Figure 8b. Once the FMS technology is mature (that is, once the production team has signficant experience in its use), a larger number of products (perhaps from several product families) may be manufactured on the FMS. This stage corresponds to the period (t_B^o, t_A^{**}) in Figure 8b.

Late in the FMS life cycle, no new products will be allocated to the FMS, and it will finish off the products already allocated to it, as in the period (t_A**, $t^{K_{AB}}$) in Figure 8b.

The observations, that compared with the Japanese, U.S. firms manufacture fewer parts on their FMS's and have invested less in the FMS technology, are consistent with a hypothesis that, at the time of Jaikumar's data collection, most U.S. FMS's were in an early stage of the FMS life cycle. In this light, observed product allocations on U.S. flexible manufacturing systems may not be suboptimal given their progress to date on the FMS life cycle. In this case, one could interpret Jaikumar's recommendations to management as instruction on how to speed the progress into the maturity phase for the use of this technology. The data on Japan's experience with the FMS technology could then be interpreted as reflecting the potential returns to accelerating the life cycle process. We make this point primarily to illustrate how our model can provide additional perspective to Jaikumar's data; we do not claim to have proven that our interpretation is unassailable.

5. CONCLUDING DISCUSSION

As was pointed out by Hayes and Wheelwright, product and process life cycle considerations can be quite important in the evaluation of technology choices. Our model of Section 2 formalizes the Hayes-Wheelwright analysis and illustrates how the cost structures of different technologies also factor into the technology choice problem.

To analyze a single firm's technology choice problem for flexible technologies, we extended our formalization of the Hayes-Wheelwright analysis to include multiple products. Our analysis focuses on the ability of flexible technology to produce a portfolio of products that are in different stages of their life cycles. We observe that optimal use of flexible technology can dictate that a narrow range of products be produced during the early and late stages of the life cycle of the technology and during the peak demand stages of the life cycles of some at the products. This observation provides an alternative interpretation of the data collected by Jaikumar (1986). More data, collected with the intent of performing a time series analysis, would be useful to help resolve these questions.

An important topic that the above models do not treat is how competition affects the technology policies we describe. One way to analyze this issue is with a game-theoretic model of technology and market competition. In our models, we assume that firm profits in each period are a function of only the level of industry demand in that period and the technology in use. A more realistic model would presume that industry growth would attract competition which would dampen (or even reverse) the effect that higher industry demand generates higher firm profits. Adding this effect could change our results in several ways. First, pre-emption incentives could cause entry into the industry to occur earlier in a multifirm game than in the single-firm model. By pre-empting its rivals with early entry, a firm might discourage later entry by others and close out some potential competition. In addition, firms would tend to enter earlier to avoid being pre-empted themselves. Second, competitive pressures might alter a firm's technology choices. Since low variable costs might allow a firm to be a "tougher" competitor, holding the capital-intensive technology might become attractive in a competitive environment. Buying the capital-intensive technology represents a commitment to stay in the industry and fight it out when competition becomes intense.

All of these ideas have been explored to some degree in the economics literature. (See Fudenberg and Tirole, 1986, for a survey.) In our view, a fruitful area for further research is to link the game-theoretic models in the economics literature to the problem of technology choice over the product life cycle and to the problem of choosing flexible versus dedicated technology.

We have begun to work towards this objective in several papers. In Fine and Li (1986), we analyze one-firm and two-firm models of optimal exit behavior with stochastic product life cycles but only one type of technology. (See also Huang and Li (1986) for a continuous-time version of the same problem.)

Fine and Pappu (1987) use the methodology of repeated games to analyze competition in a dynamic setting with both flexible and nonflexible technology. That work explores a two-firm, dynamic, stationary (no life cycles) version of the model presented in Section three. In contrast to the work here and in Fine and Freund (1987), where the absence of competition allows the existence of a flexible technology to make a firm unequivocally better off, Fine and Pappu show how the existence of a flexible technology in a competitive environment can actually make firms worse off by intensifying the competition between the firms. They also show that it can be optimal to acquire flexible technology but use it inflexibly; the flexible capability serves only as a threat to competitors to deter them from invading an incumbent's market. Further work will be required to add the product life cycle phenomenon to that model

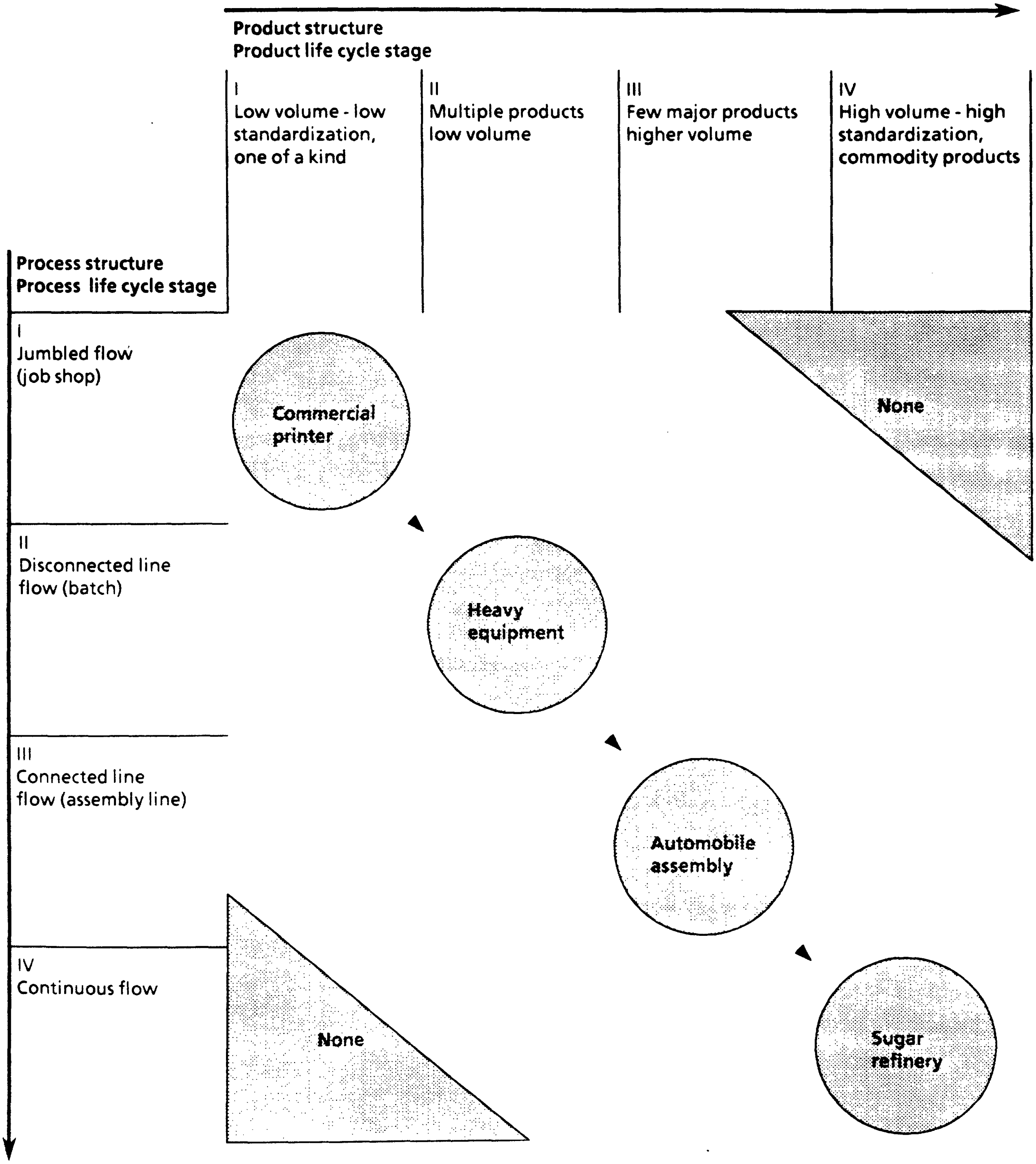

Figure 1: Product-Process Life Cycle Matrix

Source: Hayes, R.H. and S.C. Whalwright, "Link Manufacturing Process and Product Life Cycles," Harvard Business Review, January - February 1979.

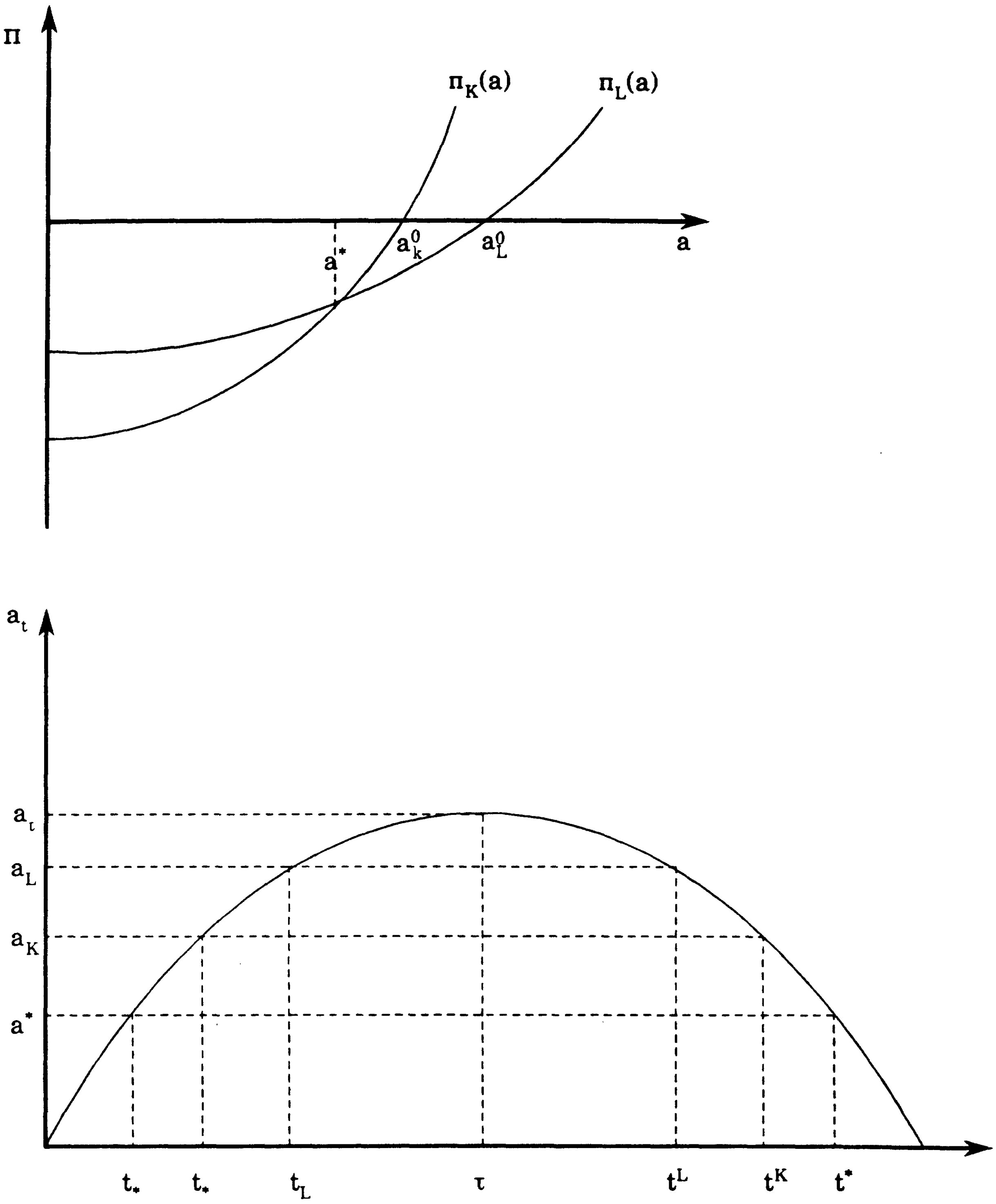

Figure 2: The Profit Functions and Demand Path when $a_K \le a_L$, the Capital Intensive Technology has a lower break even point.

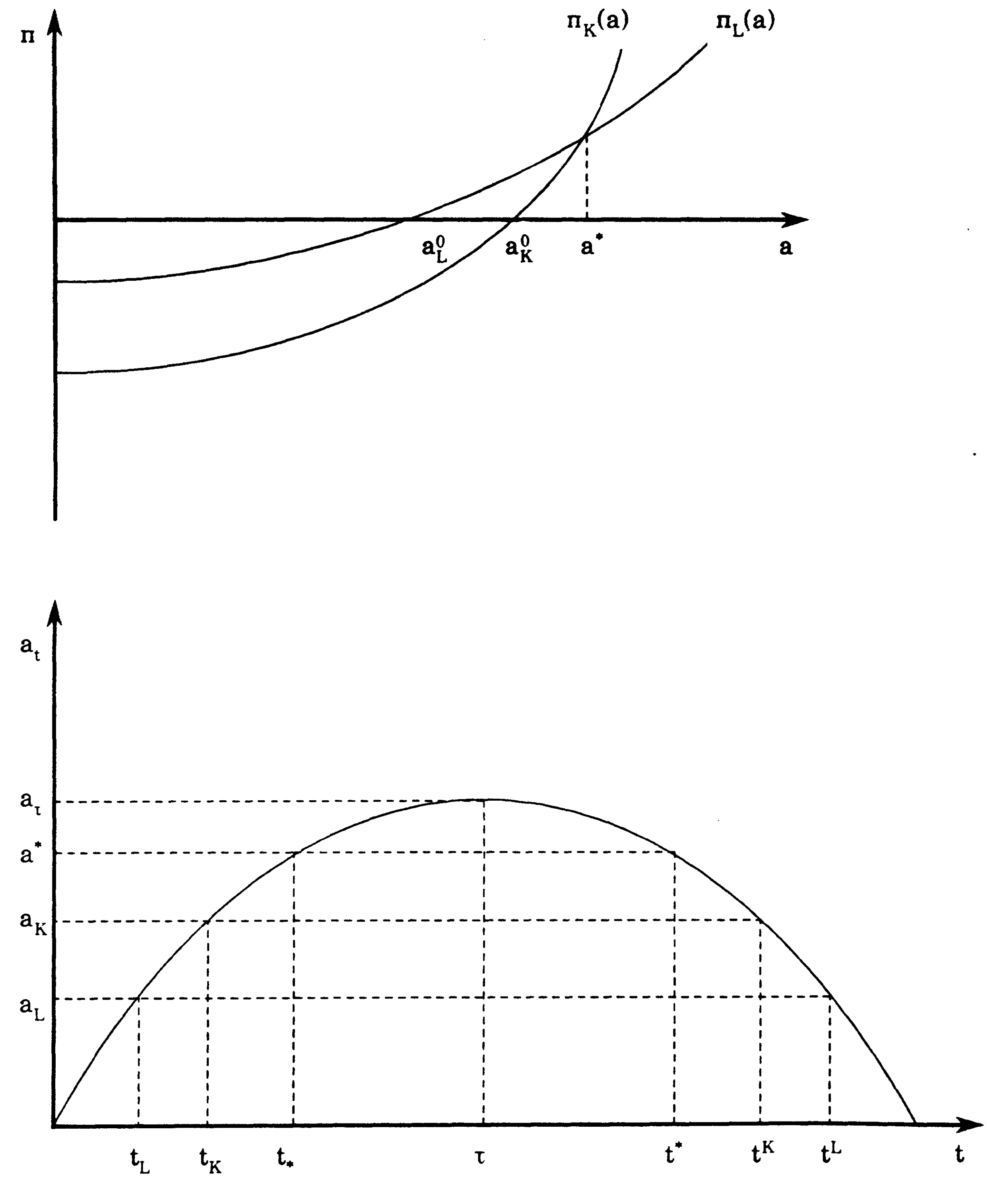

Figure 3: The Profit Functions and Demand Path when $a_K^0 > a_L^0$, the Labor-Intensive technology has a lower break even point.

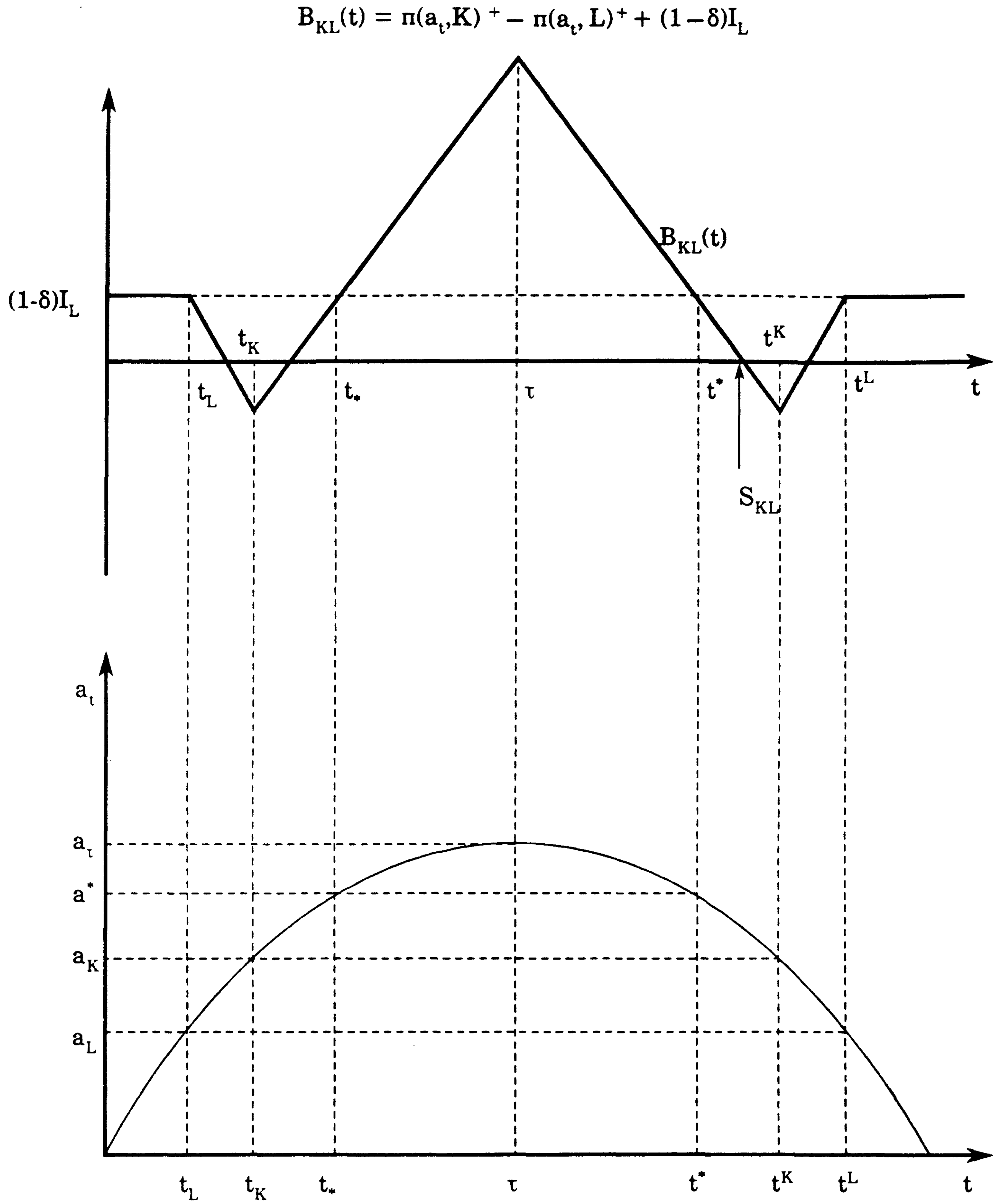

Figure 4: Determination of S_{KL}, the candidate tme for switching from the capital-intensive to the labor-intensive technology.

$$B_{LK}(t) = \pi(a_t,L)^+ - \pi(a_t,L)^+ + (1-\delta)I_K$$

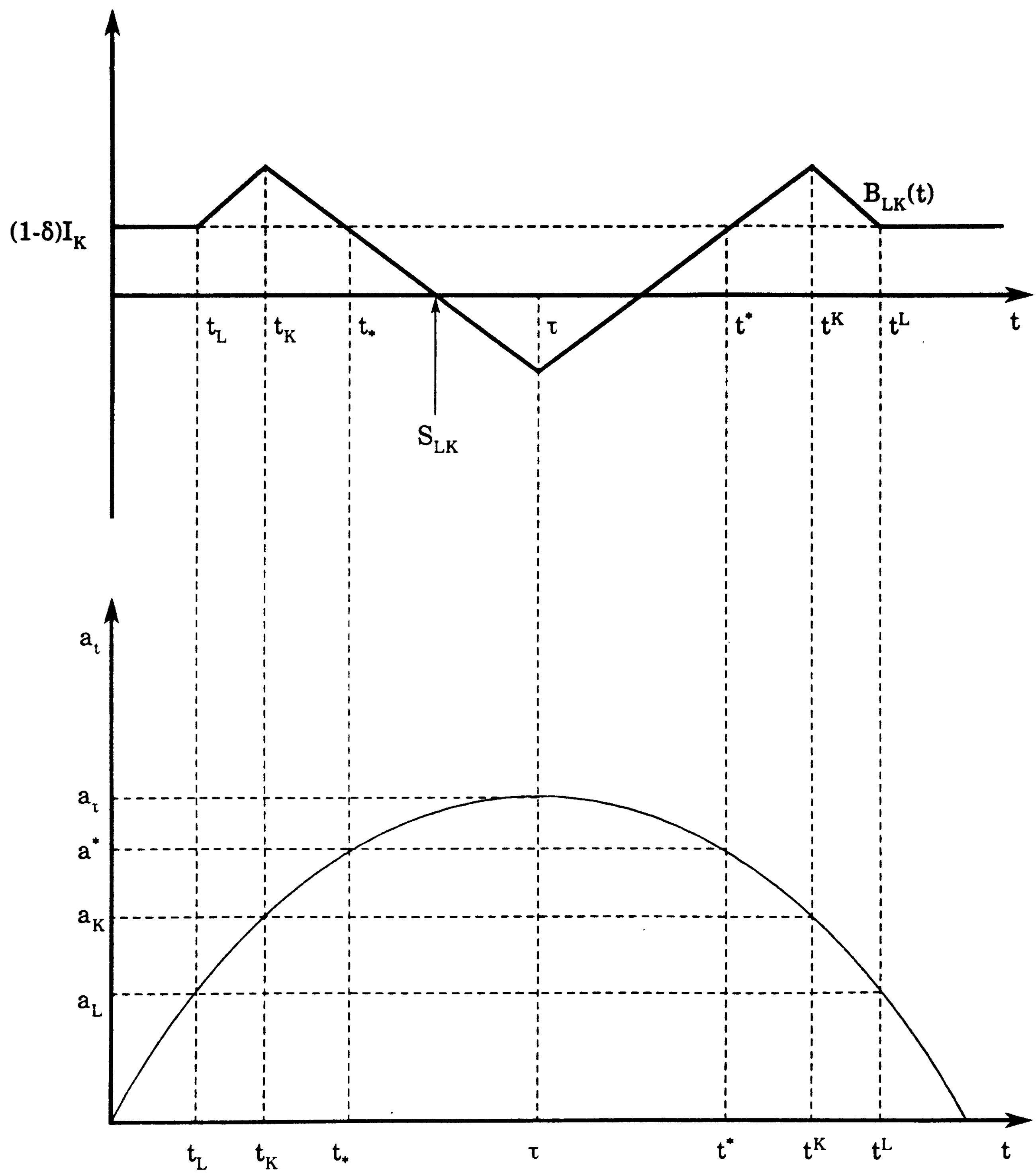

Figure 5: The Determination of S_{LK}, the candidate time for swtching from the labor intensive to the capital-intensive technology.

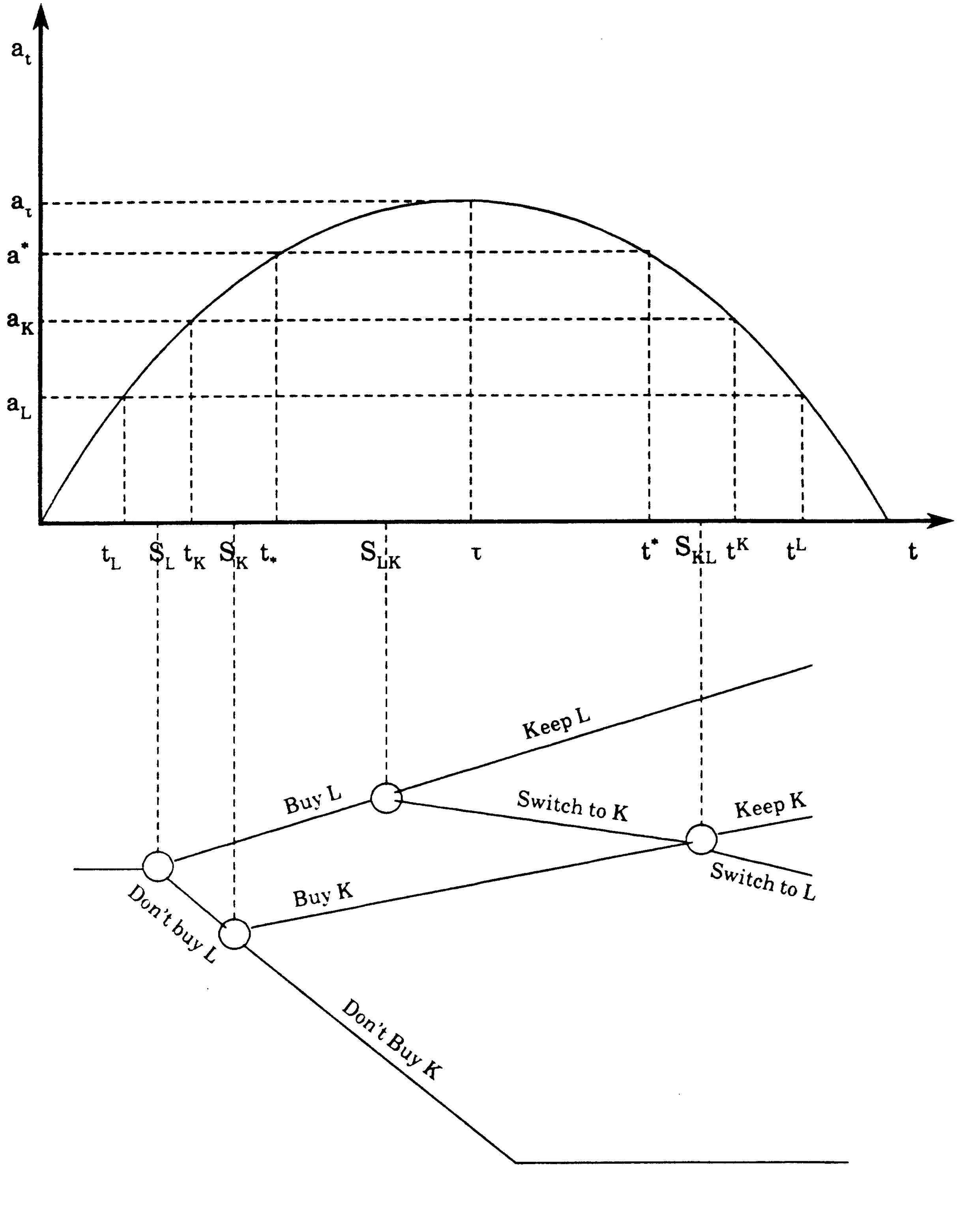

Figure 6: The Decision Tree representing the six possible optimal technology policies.

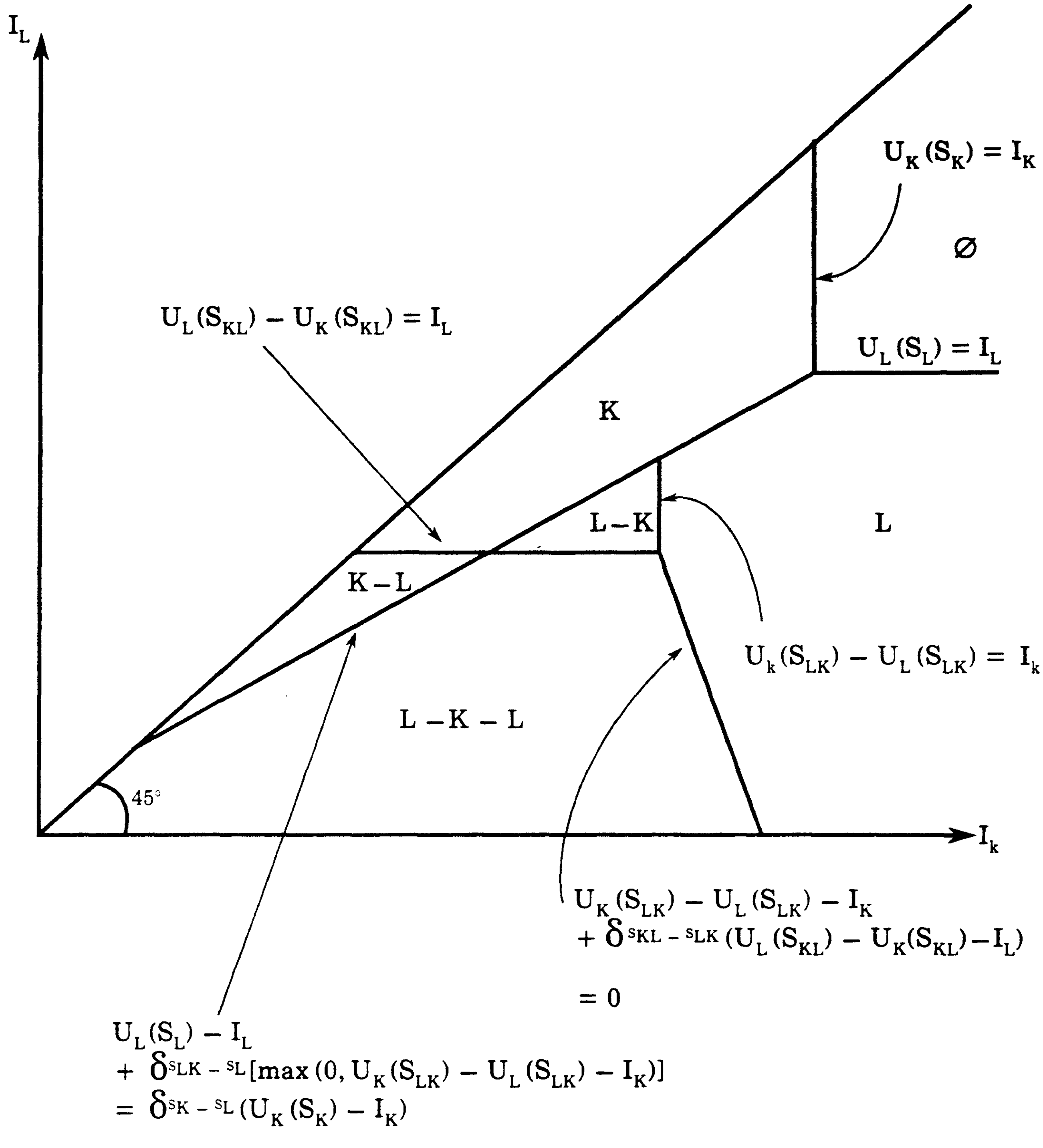

Figure 7: Determination of the optimal technology choice by the investment costs I_L and I_K.

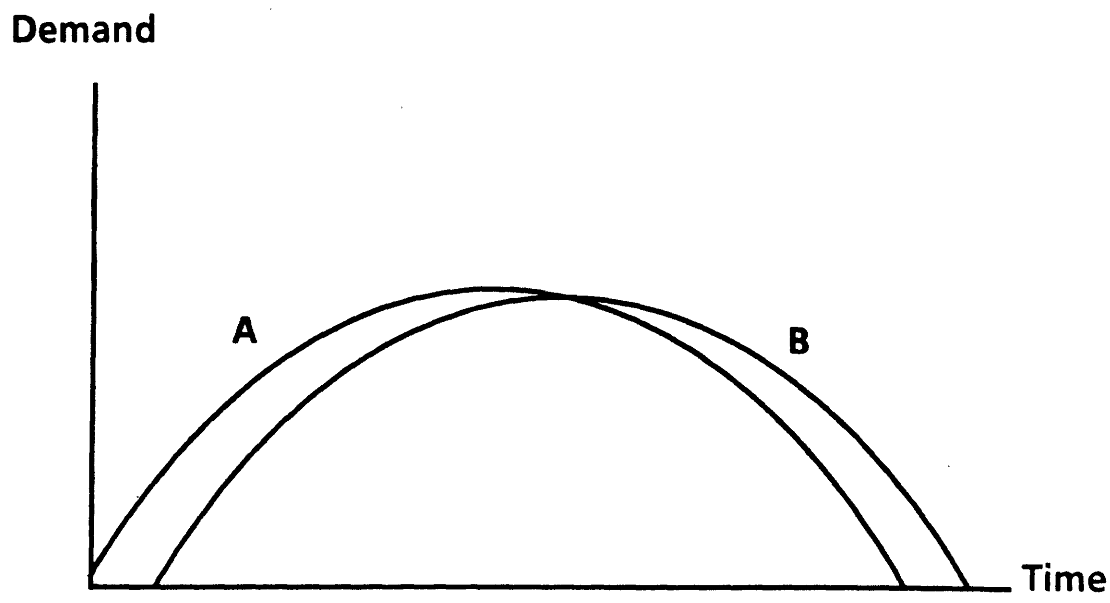

Figure 8a: Demand paths for products with synchronous life cycles.

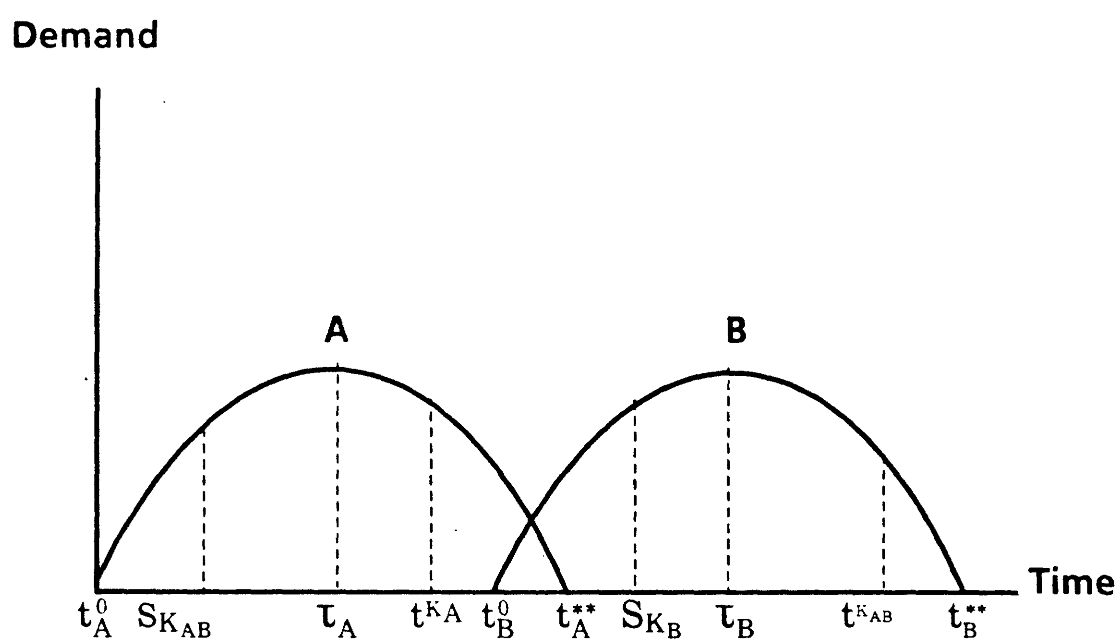

Figure 8b: Demand paths for products with asynchronous life cycles.

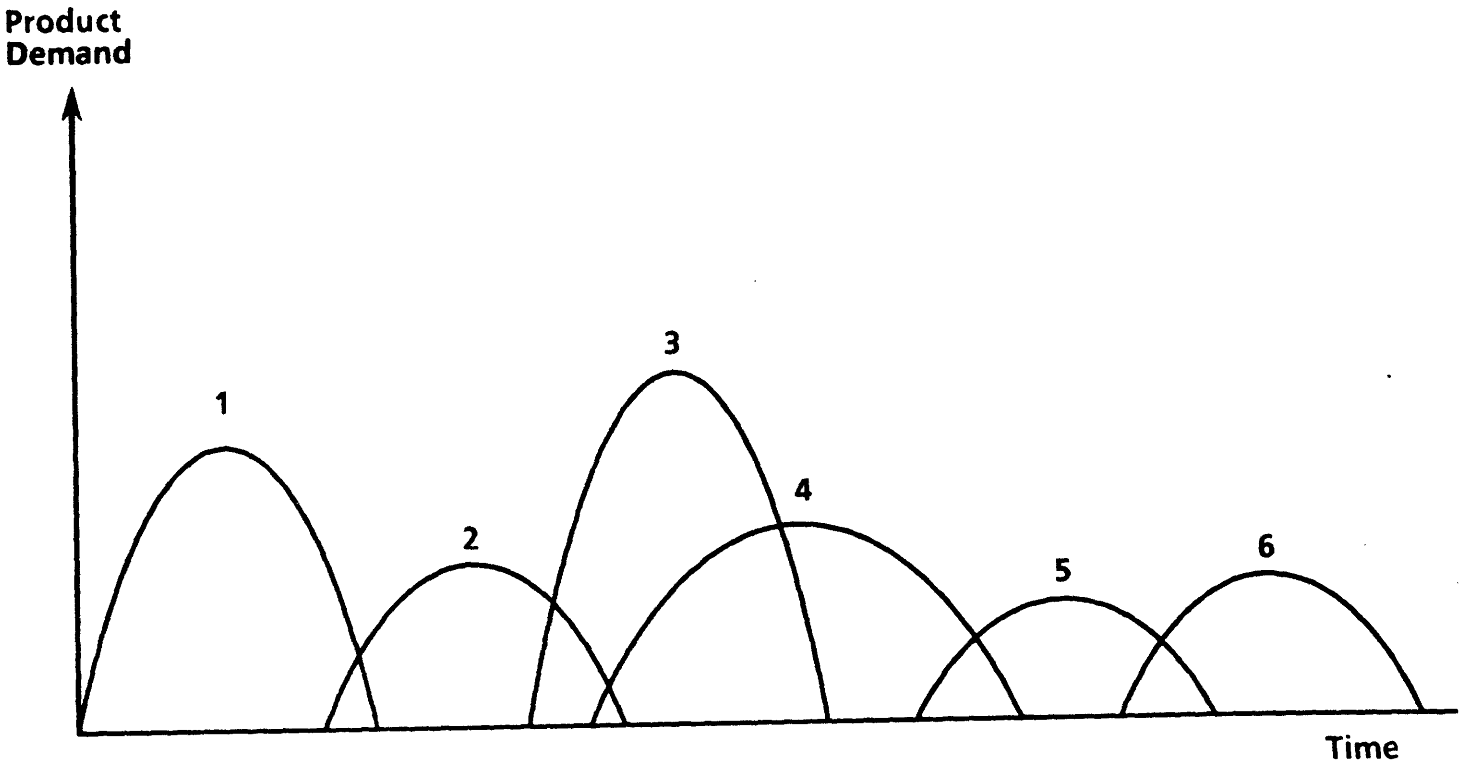

Figure 9: A Sequence of Products with Overlapping Product Life Cycles

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