MODELLING DIFFUSION OF ENERGY TECHNOLOGIES: A SYSTEM DYNAMICS APPROACH

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ABSTRACT

This paper presents an approach to model the spread of new energy technologies in an economy using System Dynamics methodology. Empirical studies on the process of technology diffusion lend evidence to sigmodial diffusion curves e.g. Gompertz's curve or logistic curve. Two major approaches reported in the literature concerning the process of technology diffusion are: 'epidemic approach' and 'probit approach'. The probit approach is closer to the reality of economic world, and has been adopted in the present model. The principle of the model is that the firms are not alike in their expectations of return on investment or risk perceptions. Hence the initial adoption of a new technology is low. But various exogenous and endogenous changes, e.g. price rise of petroleum products, brings increasing number of threshold firms into the category of actual adopters, which generates the diffusion path for the new technology. The model considers internal rate of return as the basis of such an adoption.

1. INTRODUCTION

Our world is currently experiencing a major transition to the new energy era. "Each major uprising of the long wave has had its unique technology. In energy we have had the wood-burning cycle, the coal-burning cycle, and the oil-burning cycle. Each of these has reached a crest, fallen to a minor usage, and been replaced by a new energy source and new technology. We are now nearing the end of the oil cycle" (Forrester 1979). Recent uncertainties in the oil supplies and fluctuating oil prices in the world market and persistent dependence of developing countries like India on oil imports for meeting their energy requirements underline the need for new energy supply technologies that are commercially viable alternatives to oil. Paradoxically, the spread of new energy technologies has not been fast enough. Inspite of numerous energy options available today through R & D efforts the world over, and massive organisational efforts in India like establishment of a separate Department of Non-conventional Energy Sources in the Ministry of Energy, dependence on oil has not reduced significantly. Oil demand, which had slowed down for a few years due to energy crisis of seventies, picked up again in 1976-77 and increased substantially during the end of the sixth plan-period (Government of India, Planning Commission 1985). Hence, there is a need to study the factors which influence the acceptance and usage of new technologies.

This paper presents an approach to model the spread of new energy technologies in an economy using System Dynamics methodology. Some basic concepts regarding the process of technology diffusion, as described in literature are presented. Later, based on these concepts, a system dynamics model for the diffusion of new technologies is formulated and illustrated with an example.

2. TECHNOLOGY DIFFUSION

The term "technology diffusion" signifies the spread of new technology. There are three phases in the process of technological change: invention, innovation and diffusion. Using Freeman's (1974) definitions, invention is an idea, a sketch or a model for a new improved device, product, process or system; innovation is associated with their first commercial transaction. The theory of diffusion starts at the point where the user has already innovated; it relates to the process by which the innovation spreads across the market. Empirical studies on the process of technology diffusion lend evidence to sigmodial (S-shaped) diffusion curves, e.g. Gompertz's curve or logistic curve. The well known Bass model of product life cycle also shows a S-shaped curve.

The study of the diffusion of new technologies can be categorised into three parts :

a) Intra-firm diffusion;
b) Inter-firm diffusion;
c) Economy-wide diffusion.

2.1 Intra-Firm Diffusion

Intra-firm diffusion relates to the study of time-path of use of the new technology within a firm from the introduction stage to a point where the diffusion is complete. It is a micro-level approach. Some important models of the intra-firm diffusion are: Mansfield's model (1968), Stoneman's Bayesian learning model (1981), and empirical studies, e.g. Mansfield's (1968) work on the spread of diesel locomotives in US railroads, Romeo's (1975) work on the intra-firm diffusion of numerically controlled (NC) machine tools, and Dixon's (1980) work on Hybrid corn.

2.2 Inter-Firm Diffusion

The inter-firm diffusion relates to the diffusion of technology in different firms constituting a sector. Two important approaches to the study of inter-firm or intra-sectoral diffusion are described as follows:

2.2.1 The Mansfield's Approach

The Mansfield's (1968) approach, has been labelled as 'psychological approach' or as 'epidemic approach'. This defines diffusion in terms of the number of firms using the new technology, rather than the intensity of use. This approach is based on the assumption that the use of new technology will spread as individuals make contact with one another. The diffusion curve generated is logistic. However, the model assumes that the profitability and the investment requirements remain unchanged over time. These are not valid assumptions in real life.

2.2.2 The Probit Approach

Probit models are based on the assumption that the returns to an innovation change over time. At each moment in time, firms hold the stock of new technology which is appropriate to their estimates of the returns from the use of the new technology, i.e. the firms adopt a new technology if the expected returns from its use exceed a critical value. However, all the firms are not alike and their critical level of expected returns is described by a distribution of values. There are two important models based on probit approach. David's (1969) model considers firm size as the critical parameter affecting the diffusion of new technology. Davies's (1979) model considers expected pay-off period from the use of the new technology as a critical factor for its adoption.

Probit approach is closer to the reality of the economic world, and hence adopted for modelling the technology diffusion in the present paper.

2.3 Economy-wide and International Diffusion

This category of technology diffusion covers the entire national and international economy. This analysis related to major innovations that have economy-wide applications. The epidemic and probit models as discussed earlier, may be used for study of diffusion at the economy-wide level. Some additional approaches are - the Schumpeter's approach (1934); the vintage approach, (e.g. Salter 1966); and the stock adjustment approach (e.g. Chow 1967; Nickell 1978).

3. METHODOLOGICAL FRAMEWORK

The methodology proposed in the study consists of the following steps:

a. Qualitative assessment of the future technologies based on the innovations which have already taken place or which are likely to occur in the near future using the standard techniques of technological forecasting, e.g. opinion survey, DELPHI, cross-impact analysis, etc. Such a forecast may cover the inhouse R&D efforts as well as the possibilities of technology transfer from other advanced countries. The outcome of the forecast is a kit of technologies which are the candidates of future adoption.

b. Detailed study of the cost structure, capital and labour requirements and the commercial viability of each of these technologies.

c. Study of the structural details of the economy in terms of the firm sizes, their expected rates of return, marginal cost of capital, risk perceptions and ability to raise financial resources for investment.

d. Assessment of the demand for each of these technologies based on their expected diffusion rates. It is based on the implicit assumption that a kit of all the new technologies is available for adoption, but their diffusion depends on various exogenous and endogenous factors which influence either the "stimulus variate" or the "critical level" required to elicit their adoption.

e. Modern inter-dependent production heavily relies on the flow of intermediate goods and services. Much of the technological change that occurs in one sector, leads to new methods and specifications in others. The authors have earlier developed an integrated energy model combining Leontief's input-output approach with System Dynamics (Vij et. al. 1989). The methodology proposed here for modelling technology diffusion may be used for updation of technological coefficients in input-output tables. Revised technological coefficients can be derived by augmenting the existing input-output table using the cost data of new technologies and their estimated final demand (Vij 1990).

4. MODEL DETAILS

The choice of a new technology may depend on a combination of factors e.g. relative factor prices, capital requirements, foreign exchange requirements, economic risk, environmental pollution, physical hazards, etc. However, many of the decision criteria which enter into the choice of a technology can be represented in terms of profitability, which is measured in terms of the risk adjusted internal rate of return (IROR). The proposed model is based on a single factor, i.e. the risk adjusted IROR, which simplifies the modelling process.

4.1 Flow Diagram

The flow diagram of the proposed model is shown in the Figure 1. There are two level variables in the model, i.e. User Fraction (UF) and Financial Risk (RISK). UF is the exponentially smoothed average of the

User Fraction Increase Rate (UFIR). UFIR at any point of time depends on two auxiliary variables, i.e. Risk Adjusted Rate of Return (AROR) and firms Distribution as per Cost of Capital (DCK). AROR depends on Internal Rate of Return (IROR) of the new technology adjusted for the Financial Risk (RISK). When the technology is introduced for the first time, uncertainty associated with it is high and so is the risk. However, with the passage of time, as more and more firms adopt the new technology, the risk is reduced. Risk Change Rate (RCR) is represented by an exponentially decreasing curve with a time constant LEMDA. IROR depends on the Annual Cash Flow from the new technology (ACF), Initial Capital required (IK) and Capital Life (KL). ACF is affected by the SAVING per unit of output and the Quantum of Production (OUTPUT). The new energy technologies result in savings in the energy consumer sectors. SAVING depends on the difference in production cost between the new and the old technology. It is hypothesised that the prices of non-replenishable energy resources such as the fossil fuels are likely to increase with the passage of time due to their scarcity and growing demand.

The model is driven by the energy price changes, which in turn influence the potential savings through the new energy conservation technologies. These savings influence the expected cash flow from the introduction of the new technology and the resulting IROR. The perceived risk associated with the new technology decreases with the passage of time. Hence, the firms which are initially less inclined to adopt the new technology later accept it.

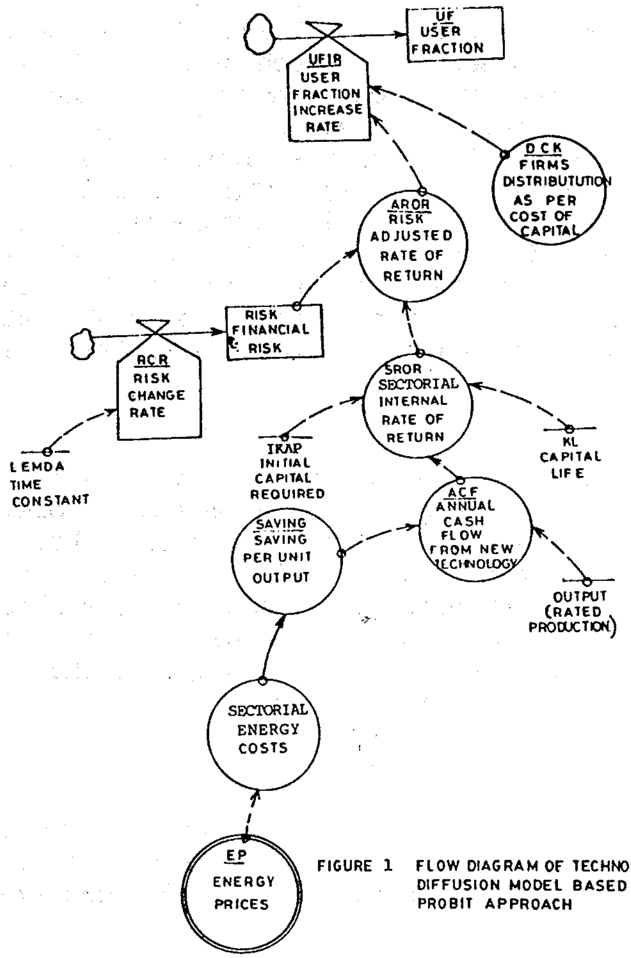

FIGURE 1 FLOW DIAGRAM OF TECHNOLOGY DIFFUSION MODEL BASED ON PROBIT APPROACH

4.2 System Equations

Based on the flow diagram shown in the previous section, system equations for the model are given below:

L UF.K = UF.J + DT (UFIR.JK) (1)

N UF = 0.0 (2)

R UFIR.KL = (ARORC.K/AROR.K)* DCK.K (3)

A AROR.K = SROR.K - RISK.K (4)

A ARORC.K = AROR.K - AROR.J (5)

A DCK.K = 0.398862 * (EXP (-Z.K * Z.K)/2) (6)

A Z.K = (CCOK.K-MEAN)/SD (7)

A CCOK.K = AROR.K (8)

C MEAN = Constant (9)

C SD = Constant (10)

where

UF -- User fraction (Dimensionless)
UFIR -- User fraction increase rate (Fraction per year)
SROR -- Sectoral rate of return from the new technology (Fraction per year)
RISK -- Financial risk (Fraction per year)
AROR -- Risk adjusted rate of return (Fraction per year)
ARORC -- Change rate of risk adjusted rate of return (Fraction per year per year)
DCK -- Distribution of firms as per cost of capital (Dimensionless)
Z -- Normal frequency distribution variate (Dimensionless)
CCOK -- Critical cost of capital (Fraction per year)
MEAN -- Mean of the normal frequency distribution of firms (Fraction per year)
SD -- Standard deviation of the normal frequency distribution of firms (Fraction per year).

Sectoral rate of return is calculated as a function based on the annual cash flow, initial capital and capital life.

A SROR.K = IROR (ACF.K, IKAP, KL) (11)

A ACF.K = SAVING.K * OUTPUT (12)

C OUTPUT = Constant (13)

where

SROR -- Sectoral rate of return (Fraction per year)
ACF -- Annual cash flow (Monetary units per year)
IKAP -- Initial capital (Monetary units)

KL -- Capital Life (years)
SAVING -- Saving per unit of output (Fraction)
OUTPUT -- Rated output from new technology (Monetary units per year)

Savings per unit depend on the reduction of cost of inputs per unit from the new technology as compared to the old technology.

A SAVING.K = (CSTEO.K - CSTEN.K) (14)

A CSTEO.K = (KPEO*PIPE.K) + (KNPEO*PINPE.K) (15)

A CSTEN.K = (KPEN*PIPE.K) + (KNPEN*PINPE.K) (16)

where

CSTEN -- Cost of energy per unit output based on new technology (Fraction)
CSTEO -- Cost of energy per unit output based on old technology (Fraction)
KPEO -- Technological coefficient of petroleum energy input based on old technology (Dimensionless)
KPEN -- Technological coefficient of petroleum energy input based on new technology (Dimensionless)
KNPEO -- Technological coefficient of non-petroleum energy input based on old technology (Dimensionless)
KNPEN -- Technological coefficient of non-petroleum energy input based on new technology (Dimensionless)
PIPE -- Price index of petroleum energy (Dimensionless)
PINPE -- Price index of non-petroleum energy (Dimensionless)

L RISK.K = RISK.J + DT (RCR.JK) (17)

R RCR.K = RISK.K * LEMDA (18)

C LEMDA = Constant (negative) (19)

where

RISK -- Financial risk (Fraction per year)
RCR -- Risk change rate (Fraction per year per year)
LEMDA -- Time Constant

5. ILLUSTRATIVE EXAMPLE

In the following paragraphs, the methodology has been explained through an illustrative example based on hypothetical data of a new technology for the industrial sector which leads to substitution of petroleum energy with power.

The new technology is initially dormant, i.e. the entire final output from the industrial sector comes from the old technology, and the user fraction (UF) of new technology is initially zero. Final demand for the new technology depends on its diffusion process. The following techno-economic parameters are assumed for the new technology:

Initial Capital (IKAP) = 2000 (monetary units)

Capital Life (KL) = 10 (years)

Rated Output (OUTPUT) = 50000 (monetary units)

Technological coefficients of energy inputs for unit output of industry in monetary terms are as follows:

	Old Technology	New Technology
Petroleum	0.010623	0.0
Power	0.019654	0.030277

Firms in the industrial sector are assumed to follow a normal distribution pattern in terms of the cost of capital with MEAN 0.10 and standard deviation 0.06.

The dynamics in the model is generated through an exponential rise in the petroleum prices, which makes the dormant technology attractive by leading to savings in the relative cost of energy inputs. The time constant of exponential increase in the petroleum sector prices is assumed to be 0.10.

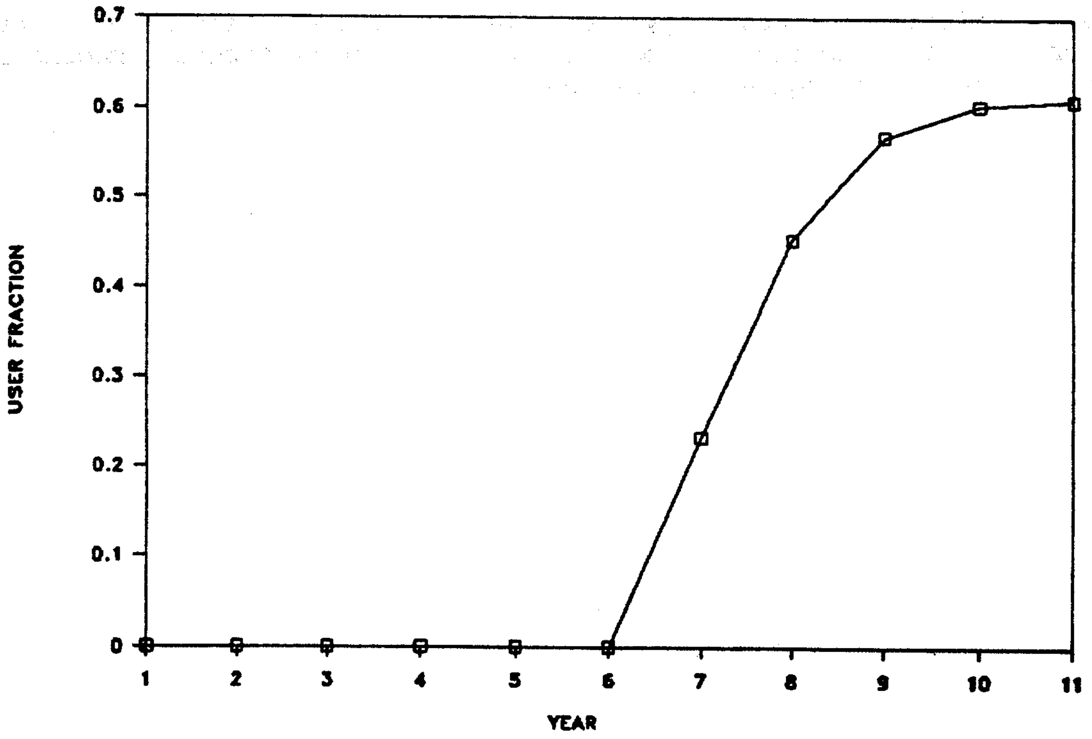

FIGURE 2 DIFFUSION CURVE OF NEW TECHNOLGOY

The diffusion curve generated with these parameters is shown in Figure 2. It shows that the new technology remains dormant for six years, after which it picks up because its IROR becomes high enough for the firms to adopt it. As IROR increases, more and more firms, even with higher cost of capital start adopting it. The demand reaches a near saturation level in the tenth year.

6. INTEGRATION WITH MULTISECTOR MODEL

The technology diffusion model described in the earlier sections is a submodel of an integrated multisector energy model. The integrated model combines Leontief's input-output approach in a physical systems theory framework with System Dynamics (Vij 1990). In the integrated model, the technological coefficients are updated every year depending on the absorption of new technology. Further, the savings are considered on the basis of difference in sectorial output costs with the new and the old technologies. These modifications result in establishing a feedback relationship between user fraction (UF) and sectorial internal rate of return (SROR).

7. CONCLUDING REMARKS

In this paper, the issues related to the representation of technological change in a multisector energy model have been discussed. Details of the flow diagrams and system equations for the technology diffusion model based on the probit approach have been explained. The technology diffusion model is based on the criteria of risk adjusted rate of return (IROR).

An illustrative example based on the hypothetical data of a new inter-fuel substitution technology for the industrial sector has been described. The approach can be incorporated with multisector models for updation of technological coefficients.

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