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A substitution orbit model of competitive innovations

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Abstract

Successful innovation and diffusion of technology can be attributed to the identification of the orbit of emerging new technologies that complement or substitute for existing technologies. This dynamism resembles the co-evolution process in an ecosystem. In an ecosystem, in order to maintain sustainable development, the complex interplay between competition and cooperation, typically observed in predator–prey systems, create a sophisticated balance. Given that an ecosystem can be used as a masterpiece system, this sophisticated balance can provide suggestive ideas for identifying an optimal orbit of competitive innovations with complement or substitution dynamism.

Prompted by such a sophisticated balance in an ecosystem, this paper analyzes the optimal orbit of competitive innovations and, on the basis of an application of Lotka-Volterra equations, it reviews substitution orbits of Japan's monochrome to color TV system, fixed telephones to cellular telephones, cellular telephones to mobile Internet access service, and analog to digital TV broadcasting. On the basis of substitution orbits analyses, it attempts to extract suggestions supportive to identifying an optimal policy option in a complex orbit leading to expected orbit.

Key findings include policy options that are effective in controlling parameters for Lotka-Volterra equations leading to expected orbit.

Keywords: Technology diffusion; Diffusion orbit; Lotka-Volterra equations; Competitive innovations; Optimal policy option

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1. Introduction

Given the global paradigm shift from an industrial society to an information society, optimal control of diffusion orbit of competitive innovations would be crucial for nation's competitiveness [1]. While advanced technologies that substitute for old technologies are usually welcomed, it is not always a simple matter to gain general consensus for the transition of such technologies [2]. Crucial issues related to the potential benefits of innovation can thus be focused on as innovation in transition [3].

"For most companies today, the only truly sustainable advantage comes from out-innovating the competition. Successful businesses are those that evolve rapidly and effectively. Yet innovative business can't evolve in a vacuum" [4]. Indeed, socioeconomic development can mainly be attributed to innovation evolved from the institutions [5–7] leading to advanced technologies that substitute for (sometimes complement with) existing technologies.

In tracing innovation diffusion, it is generally considered the spread of exchangeable mutually exclusive innovations from the ecological viewpoint, as competition between the innovations within an active social and physical environment which can be classified into the following four categories [8]:

(i) The interaction between innovations themselves on the basis of competition,
(ii) The interaction between adopters of innovations on the basis of exchange of information about the utility of innovations for adopters,
(iii) The individual's dynamic choice process, and
(iv) The interaction of an active social and physical environment in the interaction between individuals, in the choice process, and in the competition between alternative innovations.

Sonis [8] stressed that it is important to underline that the social and physical environment is active if it changes the behavior of alternatives and individuals: (i) implicitly by filtering and directing or intensifying the information flows between the individuals and between the individuals and alternatives, and (ii) explicitly by physical, social cultural, etc. restrictions and prohibitions, or by support and stimulation.

These postulates stimulate the significance of an ecosystem approach in identifying the substitution orbit of competitive innovations. Moore [4] complains that, contrary to an increasing significance, current business strategies such as networks, under the rubric of strategic alliances, virtual organizations, and the like provide little systematic assistance for managers who seek to understand the underlying strategic logic of change. He stressed the significance of a systematic approach to strategy with a view not as a member of a single industry but as part of a business ecosystem that crosses a variety of industries. In a business ecosystem, according to Moore, companies co-evolve[1] capabilities around a new innovation: they work cooperatively and competitively to support new products, satisfy customers needs,

[1] Moore refers to Gergory Rateson's definition of co-evolution that as a process in which interdependent species evolve in an endless reciprocal cycle—in which "changes in species A set the stage for the natural selection of changes in species B"—and vice versa.

and eventually incorporate the next round of innovations. Thus, focus of business priority, business ecosystem should be the process of co-evolution: the complex interplay between competitive and cooperative business strategies.

Lotka-Volterra equations analyze the behavior of two (or more) interacting species within a limited environment. As a special case, they also analyze that such complex interplay between competitive and cooperative game in an ecosystem, particularly predator–prey systems [9]. Lotka-Volterra principle for this case can be summarized as "two closely similar species will not both indefinitely be able to occupy essentially the same ecological niche, but that the slightly more successful of two will completely supplant the other eventually" [10]. Therefore, specific Lotka-Volterra systems can be supportive to the analysis of a substitution orbit of competitive innovations with complex interplay.

Prompted by such postulate, this paper analyzes the substitution orbit of competitive innovations and, on the basis of an application of a special case of Lotka-Volterra equations, it reviews substitution orbits of Japan's monochrome to color TV system, fixed telephones to cellular telephones, cellular telephones to mobile Internet access service, and analog to digital TV broadcasting. Some substitution orbits of these innovations can be traced as the diffusion orbit of a single technology, not as a part of competing or cooperating system, by applying logistic growth function, which is a simplified structure of Lotka-Volterra equations. However, it is insufficient in case of the competitive systems with complex interplay in such a shift from analog to digital TV broadcasting as it requires the complex orbit conditions including rapid shift from analog to digital TV broadcasting system and simultaneous service by both systems. An attempt to extract suggestions supportive to identifying an optimal policy option in such a complex orbit is also undertaken.

Section 2 reviews substitution orbits for transition of competitive innovations. Section 3 outlines model synthesis for two-dimensional Lotka-Volterra equations. Section 4 attempts to extract suggestions for policy option in a complex orbit. Section 5 briefly summarizes implications for the substitution orbit of competitive innovations.

2. Substitution orbit of competitive innovations

2.1. Substitution orbit: Japan's experiences

2.1.1. Substitution from monochrome to color TV system

Fig. 1 depicts the diffusion orbits of TV sets in Japan. Television broadcasting was inaugurated in Japan in 1953, followed by the color TV broadcasting in 1960. As the figure shows, the diffusion of color TV sets rapidly increased and the diffusion level of color TV sets to Japanese households exceeded that of monochrome TV sets around 1973 when color TV broadcasting became available in all TV programs.

Since the technical standard for the color TV broadcasting was compatible to monochrome TV sets, people could receive color TV broadcasting by their monochrome TV sets as monochrome TV programs. In this sense, color TV broadcasting and monochrome TV

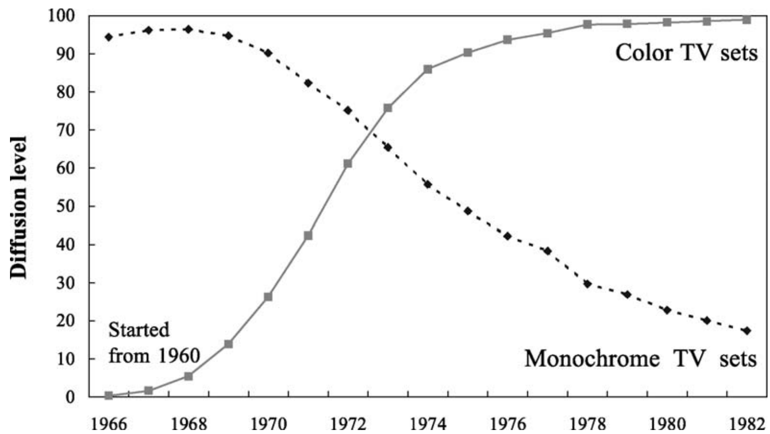

Fig. 1. Trends in the diffusion process of TV sets in Japan. Diffusion level is represented by diffusion ratio (ratio of holders and households: %). Source: "Consumer Confidence Survey," Cabinet Office, Government of Japan.

broadcasting were in a competitive relationship because people could choose either monochrome or color TV sets according to their preferences. As the price of color TV sets declined, people started to switch from monochrome to color TV sets because the function of color TV sets are clearly superior to monochrome TV sets. Consequently, color TV sets diffused rapidly in line with a logistic growth. They exhibited rapid growth from 1968, 8 years after their inauguration by substituting for monochrome TV sets.

2.1.2. Substitution from fixed telephones to cellular telephones

Fig. 2 illustrates the trends in the diffusion process of fixed telephones and their transition to cellular telephones in Japan. As the figure shows, the number of subscribers exhibited a rapid increase from the middle of the 1960s lasting two decades up to the middle of the 1980s. However, during the 1990s, it gradually stagnated and started to decrease from 1996.

The decrease or stagnation in the number of subscribers to the fixed telephone can be partly attributed to the emergence of the cellular telephones, which dramatically developed their subscribers in the 1990s triggered by deregulations such as abolishment of a deposit in 1993 and the liberalization of the sales of terminal receivers in 1994.

Fig. 2 also compares the transition of the number of subscribers to fixed telephones as well as cellular telephones from the year 1992 to 2000 in order to visualize the impact of cellular telephones to fixed telephones. At the end of the fiscal 2000, the number of subscribers to the cellular telephones exceeded that of fixed telephones.

Cellular telephones also followed a logistic growth and could achieve very rapid diffusion, 4 years after their start of substantial service because when the service became available at a reasonable price, people already well knew what the telephone is and regarded them as a complementary method to fixed telephones which cannot be used outside. Recently, some people even possess only cellular telephones because basically cellular telephones can substitute for the functionality of fixed telephones.

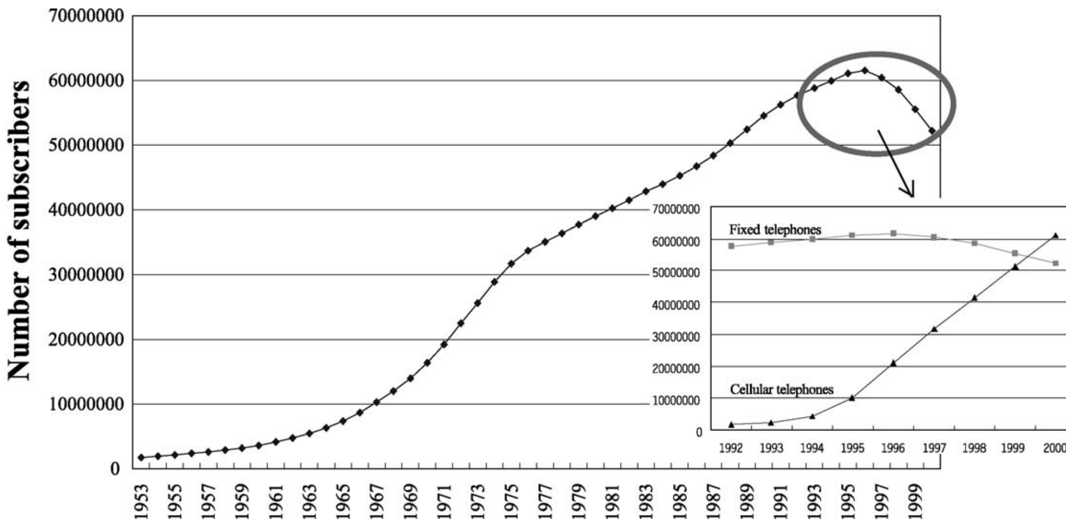

Fig. 2. Trends in the diffusion process of fixed telephones and their transition to cellular telephones in Japan (1953–2000). The part in the right-down corner of the figure illustrates transition of the number of subscribers to fixed telephones and cellular telephones.

In this sense, the relationship between fixed telephones and cellular telephones can be considered as both complementary and substitute.

2.1.3. Substitution from the cellular telephones to mobile Internet access

Fig. 3 illustrates the diffusion process of cellular telephones with and without the mobile Internet access service. The pioneer in this mobile Internet access service that enables users to access the Internet from their cellular handsets was NTT DoCoMo's *i-mode* service. While

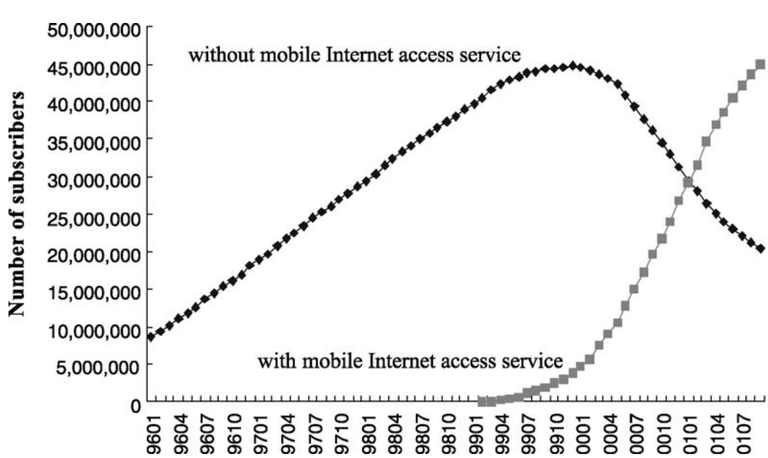

Fig. 3. Trends in the diffusion process of the cellular telephone with and without the mobile Internet access service (January 1996–September 2001). Source: Ministry of Public Management, Home Affairs, Posts and Telecommunications (MPHPT), http://www.tca.or.jp/.

the mobile Internet access also follows a logistic growth, since NTT DoCoMo introduced *i-mode* service in February 1999, this kind of mobile Internet access service has been dramatically expanding and the number of subscribers reached 31.4 million as of February 2001.

This exceptionally rapid diffusion of the mobile internet access service can be explained by such factors as (i) cellular telephones were already diffused, that is, about 40.5 million users already existed in the market when *i-mode* service was inaugurated, and (ii) potential users somewhat recognized how useful the Internet is because the Internet was getting popular in Japan.

2.1.4. Substitution from analog to digital TV broadcasting system

With the recent development of digital technology, that enabled effective error correcting, efficient data compression, and manageability of data, the TV broadcasting industry is facing a radical transitional phase—from analogue to digital system [11].

The digital TV broadcasting is highly expected to realize such advanced services as a variety of information services by data casting, interactive services which allows viewers to participate in TV programs, less deterioration in the quality of screen images, and manageable closed captions [12,13].

Realizing the potential of the digital TV broadcasting, the substitution from analog to digital broadcast system has been proceeding worldwide as illustrated in Fig. 4.

The figure demonstrates that in the US, the digital satellite broadcast started in 1994, digital cable broadcast in 1997, and digital terrestrial broadcast in 1998. As for Japan, digital satellite broadcasting started in 1996 and cable TV in 1999. However, the digital terrestrial

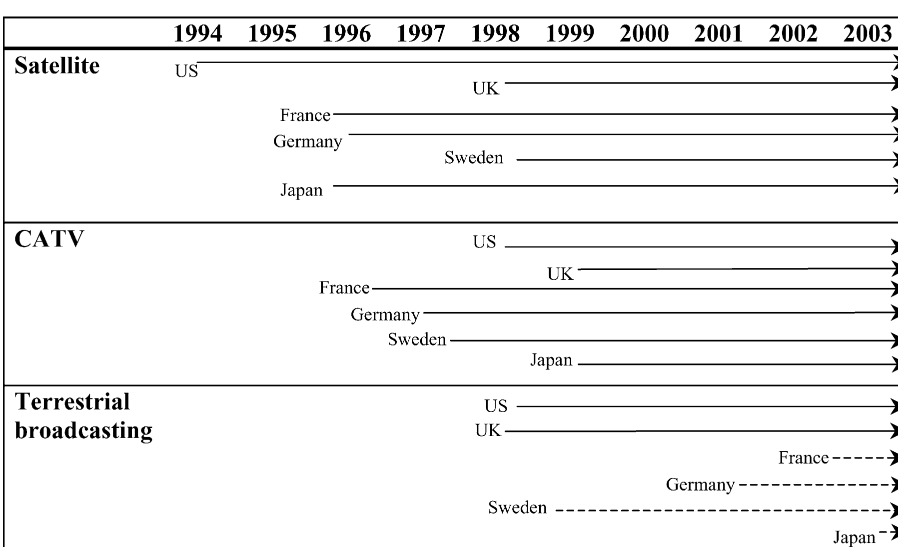

Fig. 4. Trends in the digital broadcasting worldwide. Dotted lines imply that the service is expected to start. Source: White Paper 2001 on Communications in Japan, MPHPT [14].

broadcasting is scheduled to be started in 2003, while Western Europe was somewhat quicker than Japan to move away from its previous arrangements [15].

Though the delay can be partly excused by the existence of excellent analog HDTV technology developed by NHK (the Japan Broadcasting), it is actually a great concern because the digital terrestrial broadcasting is expected to have a significant positive impact both on society and economy as TV broadcasting is one of the most familiar media with almost a 100% diffusion ratio to Japanese households. According to the report by the Advisory Committee on Digital Terrestrial Broadcasting issued in October 1998 [16], introduction of the digital terrestrial broadcast is forecasted to create about 212 trillion yen (US$1.9 trillion) economic effect and about 7 million employment in 10 years, expecting the emergence of new services using the digital broadcast characteristics.

However, the transition from analog to digital broadcasting involves huge efforts in Japan. First of all, frequency usage is fairly congested in Japan and changes in existing analog channels are inevitable in order to allot frequencies to the digital terrestrial broadcasting. This *analog channel change* considerably affects viewers and broadcasters because the channel change requires adjustments of both receivers and transmitters.

In addition, a lack of information about new technology, fear of substitution and a reluctance to pay the cost of switching to new technology generally result in disturbing smooth transition. This is particularly the case with respect to Japan's switch from analog to digital TV broadcasting because of the high popularity of television to daily life of the Japanese people.

Under the dramatic advancement of IT, while hasty transfer sometimes accomplishes nothing, delayed transfer can result in a loss of national competitiveness. Thus, policy options for the optimal shift from the analog to digital TV broadcasting have become a crucial issue for Japan.

Thus, contrary to orbits of other transition examined, the orbit for Japan's transition from analog to digital terrestrial TV broadcasting is a unique and complex one as it should satisfy the following conditions:

(i) In order to minimize the impact of a transition delay, rapid shift from analog to digital TV broadcasting is strongly expected.
(ii) As the US's experience in such shift advises, it is generally anticipated that shift from analog to digital in its initial stage is not necessarily easy.
(iii) Simultaneous service by both analog and digital broadcasting should be provided over the period between the start of the digital terrestrial TV broadcasting service and the termination of the analog terrestrial TV broadcasting.

2.2. Comparative assessment of substitution orbits

Based on the above comparative analysis, Table 1 summarizes the substitution orbits of competitive innovations: from monochrome to color TV, from fixed to cellular telephones, from cellular telephones to mobile Internet access service, and from analog to digital TV broadcasting. Looking at the table, we note that, among substitution orbits examined, years for rapid growth have dramatically shortened as new functions increased.

Table 1
Comparison of substitution orbit for transition of competitive innovations

	Complement/ substitution	Years take for rapid growth	Sources of rapid growth	Government intervention for the transition
Monochrome TV/ color TV	Substitution	8 years (logistic growth)	New function, virtuous cycle leading to cost reduction	Not substantial
Fixed telephones/ cellular telephones	Complement, partly substitution	5 years (logistic growth)	Less resistance to the new technology because of the familiarity to the existing similar technology	Deregulation
Cellular telephone/ mobile Internet access	Complement	1 year (logistic growth)	New function, less resistance to the new technology because of the familiarity to the existing similar technology	
Analog TV/ digital TV	Complementally substitution	?	New function, virtuous cycle leading to cost reduction	Substantial (vision, regulations, investment)

As reviewed in Section 1, Lotka-Volterra equations, as a special case of Lotka-Volterra systems, analyzes such the complex interplay between competitive and cooperative species in an ecosystem by solving the following differential equations:

$$\begin{aligned} \dot{x} &= x(a - bx - cy) \quad \dot{x} = \frac{\mathrm{d}x}{\mathrm{d}t} \\ \dot{y} &= y(d - ex - fy) \end{aligned} \qquad (1')$$

where x and y are species in competitive or cooperative game; a, b, c, d, e, and f are positive coefficients.

This analysis provides a supportive suggestion to the substitution orbit of competitive innovation.[2]

Provided that x is the preceding technology and y is the new succeeding technology and given that y is strong enough than x, diffusion orbit of y can be approximated by a simple logistic growth as follows:

$$\dot{y} \approx y(d - fy) \qquad (1'')$$

As reviewed in Figs. 1–3, substitution orbits of monochrome TV sets to color TV sets, fixed telephones to cellular telephones, and cellular telephones to mobile Internet access service can be traced by a logistic growth within a single innovation as can be enumerated by Eq. (1″).

However, in case of such transition from analog to digital TV broadcasting system since this transition encompasses certain stable coexistence (simultaneous stage), both x and y

[2] See Ref. [17] for flexible substitution models and the distinction between internal and external influence.

demonstrate complex interplay. This is the case of Japan's transition from analog to digital TV system, Lotka-Volterra equations are useful for analyzing this interplay by identifying controlling parameters for expected orbit.

3. Lotka-Volterra equations for substitution orbit

3.1. General orbit within Lotka-Volterra equations

Given the rate of growth of species decreases linearly as a function of the density of species, interaction of two competing species x and y can be expressed by the following Lotka-Volterra equations:

$$\dot{x} = x(a - bx - cy) = ax\left(1 - \frac{x}{a/b} - \frac{cd}{af}\cdot\frac{y}{d/f}\right) \equiv ax\left(1 - \frac{x}{k_x} - \alpha_{xy}\cdot\frac{y}{k_y}\right)$$

$$\dot{y} = y(d - ex - fy) = dy\left(1 - \frac{ae}{bd}\cdot\frac{x}{a/b} - \frac{y}{d/f}\right) \equiv dy\left(1 - \alpha_{yx}\cdot\frac{x}{k_x} - \frac{y}{k_y}\right) \quad (1)$$

where k_x ($=a/b$) and k_y ($=d/f$) are carrying capacities, α_{xy} ($=cd/af$) and α_{yx} ($=ae/bd$) are interaction coefficients, and a, b, c, d, e, f are positive coefficients (a and d: maximum diffusion scale).

Given that the orbit of x and y can be depicted by vector $V(x,y)$, and

$$V(x,y) = eH(x) + cG(y) \quad (2)$$

$$H(x) = \overline{x}\log x - x,\, G(y) = \overline{y}\log y - y \quad (3)$$

$$\frac{1}{t_n}\int_0^{t_n} x(t)\mathrm{d}t = \overline{x}\,, \frac{1}{t_n}\int_0^{t_n} y(t)\mathrm{d}t = \overline{y} \quad (4)$$

where $\overline{x}$ and $\overline{y}$: time average of x and y; t_n: the period of the solution.

From d/dt (log x)$=\dot{x}/x=a-bx-cy$.

It follows by integration that $\int_0^{t_n}\frac{\mathrm{d}}{\mathrm{d}t}\log x(t)\mathrm{d}t = \int_0^{t_n}(a - bx(t) - cy(t))\mathrm{d}t$ i.e.,

$$\log x(t_n) - \log x(0) = at_n - b\int_0^{t_n} x(t)\mathrm{d}t - c\int_0^{t_n} y(t)\mathrm{d}t$$

Since $x(t_n)=x(0)$,

$$a = b\frac{1}{t_n}\int_0^{t_n} x(t)\mathrm{d}t + c\frac{1}{t_n}\int_0^{t_n} y(t)\mathrm{d}t = b\overline{x} + c\overline{y} \quad (5)$$

Similarly,

$$d = e\bar{x} + f\bar{y} \tag{5'}$$

while $\bar{x}=(af-cd)/(bf-ce)$ and $\bar{y}=(bd-ae)/(bf-ce)$.

Thus, orbit of x and y can be represented by (Eqs. (2), (3), (5), and (5′).

The derivative of the function $V(x(t),y(t))$ by time t yields,

$$\begin{aligned}\dot{V}(x,y) &= \frac{\partial V}{\partial x}\dot{x} + \frac{\partial V}{\partial y}\dot{y} = e\dot{H}(x)\dot{x} + c\dot{G}(y)\dot{y} \\ &= e\left(\frac{\dot{x}}{x} - 1\right)\{x(a - bx - cy)\} + c\left(\frac{\bar{y}}{y} - 1\right)\{y(d - ex - fy)\}\end{aligned} \tag{6}$$

From Eqs. (5) and (5′), we may replace a and d by $b\bar{x}+c\bar{y}$ and $e\bar{x}+f\bar{y}$, respectively. This yields,

$$\begin{aligned}\dot{V}(x,y) &= e(\bar{x} - x)(b\bar{x} + c\bar{y} - bx - cy) + c(\bar{y} - y)(e\bar{x} + f\bar{y} - ex - fy) \\ &= be(x - \bar{x})^2 + 2ce(x - \bar{x})(y - \bar{y}) + cf(y - \bar{y})^2\end{aligned} \tag{7}$$

By converting coordinates from (x,y) to (X,Y) where $X=x-\bar{x}$ and $Y=y-\bar{y}$, and twisting the axis of converted coordinates to (X',Y'), Eq. (7) can be developed to an elliptical orbit (in case when $bf>ce$) or a hyperbola (in case when $ce>bf$) as expressed in Eqs. (8) and (9), respectively, by using twisted coordinates (X',Y').[3]

$$\frac{X'^2}{\left(\sqrt{\frac{\dot{V}(x,y)}{\lambda_1}}\right)^2} + \frac{Y'^2}{\left(\sqrt{\frac{\dot{V}(x,y)}{\lambda_2}}\right)^2} = 1 \qquad \text{when } bf > ce \tag{8}$$

$$\frac{X'^2}{\left(\sqrt{\frac{\dot{V}(x,y)}{\lambda_1}}\right)^2} - \frac{Y'^2}{\left(\sqrt{\frac{\dot{V}(x,y)}{-\lambda_2}}\right)^2} = 1 \qquad \text{when } ce > bf \tag{9}$$

where

$$\lambda_1 = \frac{be + cf + \sqrt{(be - cf)^2 + 4c^2e^2}}{2} \tag{10}$$

$$\lambda_2 = \frac{be + cf - \sqrt{(be - cf)^2 + 4c^2e^2}}{2} \tag{11}$$

[3] See Ref. [18] for the mathematical details and qualitative analysis of nonlinear systems by Lotka-Volterra approach.

In order to identify twisted coordinates (X',Y'), the twisted angle θ should be measured, which is expressed by the following equations (see mathematical development 3.2):

$$\cos\theta = \frac{1}{\sqrt{1+\frac{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}{2c^2e^2}}} \tag{12}$$

$$\sin\theta = \frac{1}{\sqrt{1+\frac{2c^2e^2}{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}}} \tag{13}$$

where $\omega = be - cf$.

3.2. Factors governing the twisting of an orbit

Provided that coefficients matrix of Eq. (7) **A** can be depicted as follows:

$$\mathbf{A} = \begin{bmatrix} be & ce \\ ce & cf \end{bmatrix} \tag{14}$$

By using **A**, Eq. (7) can be depicted as follows:

$$\dot{V}(x,y) = {}^t\mathbf{x}\mathbf{A}\mathbf{x} \qquad \mathbf{x} = \begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} x-\bar{x} \\ y-\bar{y} \end{bmatrix} \tag{15}$$

In identify factors governing the twisting angle θ, first, calculating determinants of matrix **A**:

$$|x\mathbf{E}-\mathbf{A}| = \begin{bmatrix} x-be & -ce \\ -ce & x-cf \end{bmatrix} = (x-be)(x-cf) - c^2e^2 = 0 \tag{16}$$

leads to the following equation:

$$x^2 - (be+cf)x + bcef - c^2e^2 = 0 \tag{17}$$

Solving Eq. (17), results in two eigen values for determinant of matrix **A** as follows:

$$\lambda_1 = \frac{be + cf + \sqrt{(be+cf)^2 - 4bcef + 4c^2e^2}}{2},$$

$$\lambda_2 = \frac{be + cf - \sqrt{(be+cf)^2 - 4bcef + 4c^2e^2}}{2} \tag{18}$$

The next step is to calculate the eigen vectors [$\mathbf{v}_1$ and $\mathbf{v}_2$] for matrix **A**. Since eigen values λ_1 and λ_2 are already known, two different cases can be considered.
(i) If $\lambda = \lambda_1$, then $\mathbf{A}\mathbf{v}_1 = \lambda_1\mathbf{v}_1$.

$$\begin{bmatrix} be & ce \\ ce & cf \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \end{bmatrix} = \lambda_1 \begin{bmatrix} X_1 \\ Y_1 \end{bmatrix} \tag{19}$$

$$\begin{cases} beX_1 + ceY_1 = \lambda_1 X_1 \\ ceX_1 + cfY_1 = \lambda_1 Y_1 \end{cases} \tag{20}$$

$$\begin{cases} (be - \lambda_1)X_1 + ceY_1 = 0 \\ ceX_1 + (cf - \lambda_1)Y_1 = 0 \end{cases} \tag{21}$$

$$\mathbf{v}_1 = \begin{bmatrix} X_1 \\ Y_1 \end{bmatrix} = k_1 \begin{bmatrix} ce \\ \lambda_1 - be \end{bmatrix} \qquad (k_1 \neq 0) \tag{22}$$

(ii) If $\lambda = \lambda_2$, then $\mathbf{A}\mathbf{v}_1 = \lambda_2\mathbf{v}_1$.
Following the same simple algebraic steps as in case (i):

$$\mathbf{v}_2 = \begin{bmatrix} X_1 \\ Y_2 \end{bmatrix} = k_2 \begin{bmatrix} ce \\ \lambda_2 - be \end{bmatrix} \qquad (k_2 \neq 0) \tag{23}$$

The above eigen vectors $\mathbf{v}_1$ and $\mathbf{v}_2$ are linearly independent and they are perpendicular vectors forming a right angle ($k_1 \neq 0$ and $k_2 \neq 0$).

$$\mathbf{v}_1 = \begin{bmatrix} X_1 \\ Y_1 \end{bmatrix} = k_1 \begin{bmatrix} ce \\ \lambda_1 - be \end{bmatrix} \tag{24}$$

The magnitude of vector $\mathbf{v}_1$ is calculated as follows:

$$||\mathbf{v}_1|| = \sqrt{(cek_1)^2 + \left\{(\lambda_1 - be)k_1\right\}^2} = \sqrt{\left\{c^2e^2 + (\lambda_1 - be)^2\right\}k_1^2} \tag{25}$$

If $||\mathbf{v}_1|| = 1$, then

$$\sqrt{\left\{c^2e^2 + (\lambda_1 - be)^2\right\}k_1^2} = 1 \tag{26}$$

and

$$k_1 = \pm\frac{1}{\sqrt{c^2e^2 + (\lambda_1 - be)^2}}. \tag{27}$$

Similarly,

$$k_2 = \pm\frac{1}{\sqrt{c^2e^2 + (\lambda_2 - be)^2}} \tag{28}$$

Considering the positive options for k_1 and k_2:

$$k_1 = \frac{1}{\sqrt{c^2e^2 + (\lambda_1 - be)^2}}, k_2 = -\frac{1}{\sqrt{c^2e^2 + (\lambda_2 - be)^2}} \tag{29}$$

Substituting Eq. (29) for k_1 and k_2 in Eqs. (22) and (23), two new vectors are derived:

$$\mathbf{u}_1 = \frac{1}{\sqrt{c^2e^2 + (\lambda_1 - be)^2}}\begin{bmatrix} ce \\ \lambda_1 - be \end{bmatrix} = \begin{bmatrix} \frac{ce}{\sqrt{c^2e^2+(\lambda_1-be)^2}} \\ \frac{\lambda_1-be}{\sqrt{c^2e^2+(\lambda_1-be)^2}} \end{bmatrix} \tag{30}$$

$$\mathbf{u}_2 = \frac{1}{\sqrt{c^2e^2 + (\lambda_2 - be)^2}}\begin{bmatrix} ce \\ \lambda_2 - be \end{bmatrix} = \begin{bmatrix} -\frac{ce}{\sqrt{c^2e^2+(\lambda_2-be)^2}} \\ -\frac{\lambda_2-be}{\sqrt{c^2e^2+(\lambda_2-be)^2}} \end{bmatrix} \tag{31}$$

Matrix $\mathbf{U}$ is composed of the two vectors in Eqs. (30) and (31):

$$\mathbf{U} = [\mathbf{u}_1\ \mathbf{u}_2] = \begin{bmatrix} \frac{ce}{\sqrt{c^2e^2+(\lambda_1-be)^2}} & -\frac{ce}{\sqrt{c^2e^2+(\lambda_2-be)^2}} \\ \frac{\lambda_1-be}{\sqrt{c^2e^2+(\lambda_1-be)^2}} & -\frac{\lambda_2-be}{\sqrt{c^2e^2+(\lambda_2-be)^2}} \end{bmatrix} \tag{32}$$

Simplifying Eq. (18) as follows,

$$\lambda_1 = \frac{be+cf+\sqrt{(be+cf)^2-4bcef+4c^2e^2}}{2} = \frac{be+cf+\sqrt{(be-cf)^2+4c^2e^2}}{2} \tag{33}$$

$$\lambda_2 = \frac{be+cf-\sqrt{(be+cf)^2-4bcef+4c^2e^2}}{2} = \frac{be+cf-\sqrt{(be-cf)^2+4c^2e^2}}{2} \tag{34}$$

we get:

$$\lambda_1 - be = \frac{-be+cf+\sqrt{(be-cf)^2+4c^2e^2}}{2} = \frac{-(be-cf)+\sqrt{(be-cf)^2+4c^2e^2}}{2} > 0 \tag{35}$$

$$\lambda_2 - be = \frac{-be+cf-\sqrt{(be-cf)^2+4c^2e^2}}{2} = \frac{-(be-cf)-\sqrt{(be-cf)^2+4c^2e^2}}{2} < 0 \tag{36}$$

Since $ce>0$, $\lambda_1 - be>0$, $\lambda_2 - be<0$, rewriting Eq. (32) leads to the following matrix:

$$\mathbf{U} = \begin{bmatrix} \frac{ce}{\sqrt{c^2e^2+(\lambda_1-be)^2}} & -\frac{ce}{\sqrt{c^2e^2+(\lambda_2-be)^2}} \\ \frac{\lambda_1-be}{\sqrt{c^2e^2+(\lambda_1-be)^2}} & -\frac{\lambda_2-be}{\sqrt{c^2e^2+(\lambda_2-be)^2}} \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{1+\frac{(\lambda_1-be)^2}{c^2e^2}}} & -\frac{1}{\sqrt{1+\frac{(\lambda_2-be)^2}{c^2e^2}}} \\ \frac{1}{\sqrt{\frac{c^2e^2}{(\lambda_1-be)^2}+1}} & \frac{1}{\sqrt{\frac{c^2e^2}{(\lambda_2-be)^2}+1}} \end{bmatrix} \tag{37}$$

From Eq. (37),

$$(\lambda_1 - be)^2 = \left(\frac{-(be-cf)+\sqrt{(be-cf)^2+4c^2e^2}}{2}\right)^2 = \left(\frac{-\omega+\sqrt{\omega^2+4c^2e^2}}{2}\right)^2$$

$$= \frac{2\omega^2 - 2\omega\sqrt{\omega^2+4c^2e^2}+4c^2e^2}{4} = \frac{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}{2} \tag{38}$$

Suppose

$$be - cf = \omega, \tag{39}$$

then

$$(\lambda_2 - be)^2 = \left(\frac{-(be-cf)-\sqrt{(be-cf)^2+4c^2e^2}}{2}\right)^2$$

$$= \left(\frac{-\omega-\sqrt{\omega^2+4c^2e^2}}{2}\right)^2 = \frac{2\omega^2+2\omega\sqrt{\omega^2+4c^2e^2}+4c^2e^2}{4}$$

$$= \frac{\omega^2+2c^2e^2+\omega\sqrt{\omega^2+4c^2e^2}}{2}$$

$$= \left(\frac{\omega^2+2c^2e^2+\omega\sqrt{\omega^2+4c^2e^2}}{2}\right)\left(\frac{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}\right)$$

$$= \frac{\left(\omega^2+2c^2e^2\right)^2-\left(\omega\sqrt{\omega^2+4c^2e^2}\right)^2}{2\left(\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}\right)}$$

$$= \frac{\omega^4+4c^2e^2\omega^2+4c^4e^4-\left(\omega^4+4c^2e^2\omega^2\right)}{2\omega^2+4c^2e^2-2\omega\sqrt{\omega^2+4c^2e^2}}$$

$$= \frac{4c^4e^4}{2\omega^2+4c^2e^2-2\omega\sqrt{\omega^2+4c^2e^2}} = \frac{2c^4e^4}{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}} \tag{40}$$

Substituting $(\lambda_2 - be)^2$ with $\frac{2c^4e^4}{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}$ and inserting that in Eq. (37):

$$\mathbf{U} = \begin{bmatrix} \frac{1}{\sqrt{1+\frac{(\lambda_1-be)^2}{c^2e^2}}} & -\frac{1}{\sqrt{1+\frac{(\lambda_2-be)^2}{c^2e^2}}} \\ \frac{1}{\sqrt{\frac{c^2e^2}{(\lambda_1-be)^2}+1}} & \frac{1}{\sqrt{\frac{c^2e^2}{(\lambda_2-be)^2}+1}} \end{bmatrix}$$

$$= \begin{bmatrix} \frac{1}{\sqrt{1+\frac{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}{2}\cdot\frac{1}{c^2e^2}}} & -\frac{1}{\sqrt{1+\frac{2c^4e^4}{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}\cdot\frac{1}{c^2e^2}}} \\ \frac{1}{\sqrt{c^2e^2\cdot\frac{2}{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}+1}} & \frac{1}{\sqrt{c^2e^2\cdot\frac{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}{2c^4e^4}+1}} \end{bmatrix}$$

$$= \begin{bmatrix} \frac{1}{\sqrt{1+\frac{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}{2c^2e^2}}} & -\frac{1}{\sqrt{1+\frac{2c^2e^2}{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}}} \\ \frac{1}{\sqrt{1+\frac{2c^2e^2}{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}}} & \frac{1}{\sqrt{1+\frac{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}{2c^2e^2}}} \end{bmatrix} \quad (41)$$

From Eq. (41), twisting angle θ can be calculated as follows:

$$\cos\theta = \frac{1}{\sqrt{1+\frac{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}{2c^2e^2}}}, \quad \sin\theta = \frac{1}{\sqrt{1+\frac{2c^2e^2}{\omega^2+2c^2e^2-\omega\sqrt{\omega^2+4c^2e^2}}}} \quad (42)$$

3.3. General image of an elliptical orbit

Based on the foregoing mathematical analysis, an orbit of competing technologies x, y with certain interplay conditions can be depicted as follows, and general image of an elliptical orbit under certain $\dot{V}$ condition (in case of $bf > ce$) can be illustrated as Fig. 5:

Interplay conditions

$$\dot{x} = x(a - bx - cy)$$

$$\dot{y} = y(d - ex - fy)$$

Orbit,

$$\dot{V}(x,y) = be(x-\bar{x})^2 + 2ce(x-\bar{x})(y-\bar{y}) + cf(y-\bar{y})^2$$

$$\frac{X'^2}{\left(\sqrt{\frac{\dot{V}(x,y)}{\lambda_1}}\right)^2} + \frac{Y'^2}{\left(\sqrt{\frac{\dot{V}(x,y)}{\lambda_2}}\right)^2} = 1$$

$$\lambda_1 = \frac{be + cf + \sqrt{(be + cf)^2 - 4bcef + 4c^2e^2}}{2},$$

$$\lambda_2 = \frac{be + cf - \sqrt{(be + cf)^2 - 4bcef + 4c^2e^2}}{2}$$

Twisting angle,

$$\cos\theta = \frac{1}{\sqrt{1 + \frac{\omega^2 + 2c^2e^2 - \omega\sqrt{\omega^2 + 4c^2e^2}}{2c^2e^2}}}$$

$$\sin\theta = \frac{1}{\sqrt{1 + \frac{2c^2e^2}{\omega^2 + 2c^2e^2 - \omega\sqrt{\omega^2 + 4c^2e^2}}}}$$

where $\omega = be - cf$.

Given the technologies, x and y compete with each other by constructing a complex orbit following the foregoing conditions, Fig. 5 provides suggestive idea for optimal policy option.

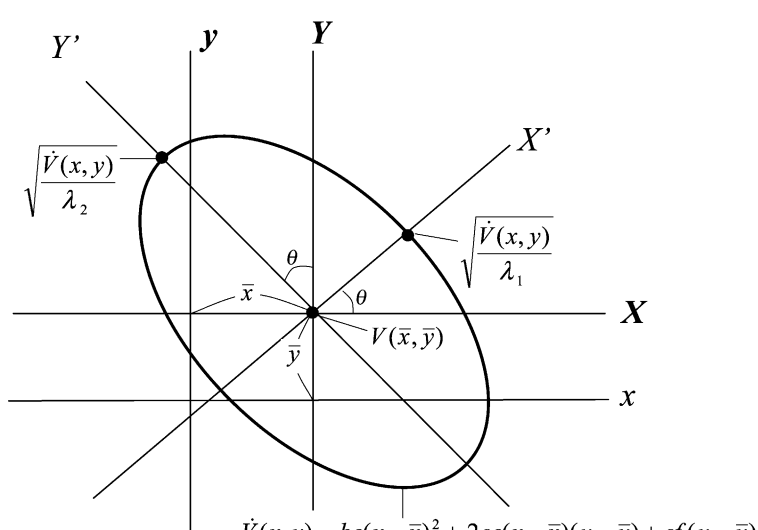

Fig. 5. General image of an elliptical orbit.

4. Orbit for substitution—policy option in a complex orbit

While there exists variety of orbits in predator–prey systems [19,20] given such transition as anticipated in shift from analog to digital TV broadcasting analyzed in Section 2, following boundary conditions are imposed.

Provided that a species x is a preceding species and, later on, a species y appears and steadily succeeds x, and finally substitutes for x, an orbit for y substitute for x can be developed as follows.

In general interaction of two competing species x and y, interaction coefficients in Eq. (1′) $\alpha_{xy}(=cd/af)$ and $\alpha_{yx}(=ae/bd)$ are,

$$\begin{array}{ll} 1 \geq \alpha_{xy} > 0 & \text{i.e. } a/c \geq d/f \\ 1 \geq \alpha_{yx} > 0 & \text{i.e } d/e \geq a/b \end{array} \tag{43}$$

A condition of the initial stage just before the substantial emergence of species y can be depicted as $\partial\dot{V}/\partial y=0$, i.e.,

$$\begin{array}{l} \dfrac{\partial\dot{V}}{\partial y} = 2ce(x-\overline{x}) + 2cf(y-\overline{y}) = 0 \\ e(x-\overline{x}) + f(y-\overline{y}) = 0 \\ ex + fy = e\overline{x} + f\overline{y} = d \end{array} \tag{44}$$

Eq. (1′) suggests that this is equivalent to $\dot{y}/y=0$.

Similarly, a condition of the stage when y totally substitutes for x can be depicted as $\partial\dot{V}/\partial x=0$, i.e.,

$$bx + cy = b\overline{x} + c\overline{y} = a \tag{45}$$

This is equivalent to $\dot{x}/x=0$.

Given a case of such shift as from analog to digital broadcasting as analyzed in Section 2.1, Eq. (43) depicts conditions (i) and (ii), while Eqs. (44) and (45) depict conditions (iii) and (iv), respectively. Condition (v) requires that a simultaneous solution of Eqs. (38) and (39) exists under the condition of x, y>0.

The isoclines of the above dynamism that satisfy conditions enumerated by Eqs. (43)–(45) can be illustrated as Fig. 6:

Under the condition that x, y>0 (hence, $\overline{x}$, $\overline{y}$>0) and given the case when y succeeds x, $d/e \geq a/b$ as well as $a/c \geq d/f$ and hence $b/e \geq a/d \geq c/f$ conditions should be satisfied which lead to $bf > ce$.

These conditions imply the followings with respect to an orbit of two-dimensional Lotka-Volterra equations for y substitutes for x:

(i) The orbit follows an elliptical orbit,
(ii) Relationship between x and y is the case of stable coexistence, and
(iii) Equilibrium point of this coexistence $V(x, y) = V(\overline{x}, \overline{y})$.

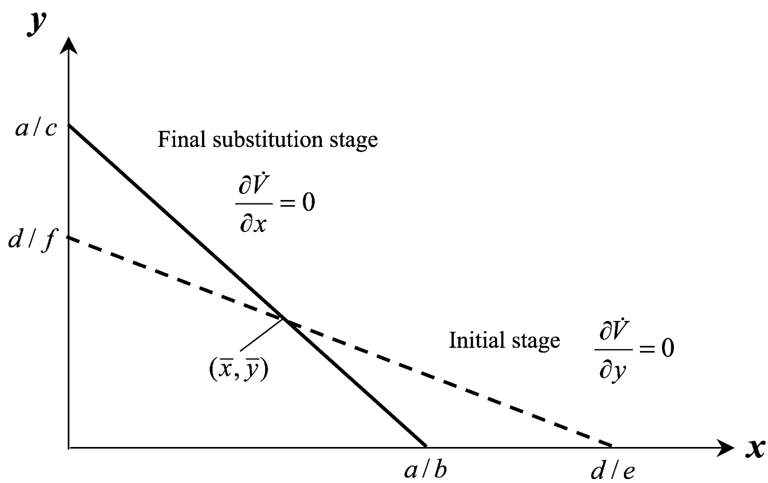

Fig. 6. Isoclines for two-dimensional Lotka-Volterra equations.

Under the above dynamism, given the situation when y totally substitutes for x at the final substitution stage, $\bar{x} = 0$ and hence $a/c = d/f$ should be satisfied which implies the followings with respect to an orbit in the period starting from the initial stage when y first invades into x ($\partial \dot{V}/\partial y = 0$) and ending final substitution stage when y totally substitutes for x ($\partial \dot{V}/\partial x = 0$):

(i) The orbit $V(x, y)$ moves from $V(d/e, 0)$ to $V(0, a/c)$, and
(ii) The interaction coefficient $\alpha_{xy}(cd/df) = 1$ (see Eq. (1′)) while $\alpha_{yx}(= ae/bd) < 1$. (This implies y's invasion power into x territory is stronger than that of x into y.)

Thus, isoclines for two-dimensional Lotka-Volterra equations under substitution orbit can be illustrated as Fig. 7.

As general two-dimensional game suggests, after certain game, $\dot{V}$ stagnates steadily and reaching $\dot{V} = 0$,[4] by synchronizing Figs. 5 and 7, general image of an elliptical orbit for substitution can be illustrated as Fig. 8.

Under the condition when $V(x,y)$ shifts to the state of equilibrium with respect to y substitution for x with certain constant pace,[5] an orbit of Fig. 5 can be projected to respective

[4] This implies the state of equilibrium with respect to y substitution for x, and does not imply the termination of y or x increase.

[5] By differentiating $\dot{V}(x,y)$ in Eq. (7) by time t, we obtain:

$$\frac{\mathrm{d}\dot{V}(x,y)}{\mathrm{d}t} = -2\left\{ex(a - bx - cy)^2 + cy(d - ex - fy)^2\right\} \leq 0$$

$$\frac{\mathrm{d}\dot{V}(x,y)}{\mathrm{d}t} = 0 \text{ when } \dot{V}(x,y) = \dot{V}(\bar{x}, \bar{y}).$$

This suggests that an orbit $\dot{V}(x,y)$ shifts toward the equilibrium point $\dot{V}(\bar{x},\bar{y})$ with a pace of $g(\equiv -2\{ex(a - bx - cy)^2 + cy(d - ex - fy)^2\})$. Given a constant g, $\dot{V}(x,y)$ can be depicted as $\dot{V}(x,y) = \dot{V}_0(x,y)e^{gt}$ where $\dot{V}_0(x,y)$ indicates initial change.

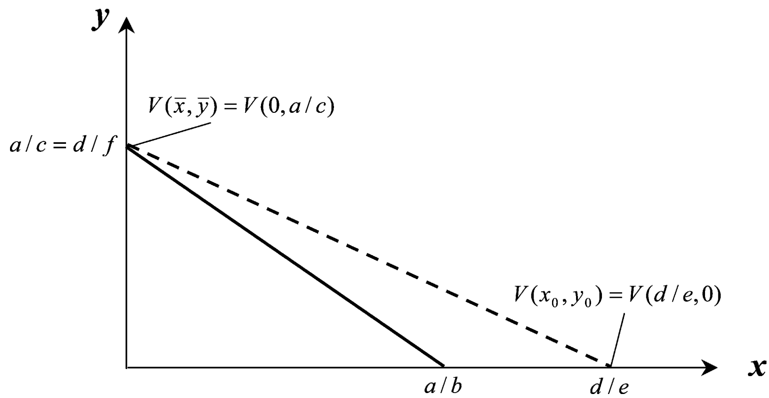

Fig. 7. Isoclines for two-dimensional Lotka-Volterra equations under substitution orbit.

time trend of x and y as illustrated in Fig. 9. In this case, time scale t differs whether it is "market time scale" or "innovation time scale." In case of the latter scale, diffusion of new innovation y is generally slow, but if it is less complex, encompasses a possibility of rapid diffusion which cannot be expected under "market time scale" as is observed in the transition from monochrome TV to color TV (Fig. 1). Provided that diffusion y is expected to be forwarded promptly as reviewed in Section 2.1.4, y should be concave in an innovative time scale and this could be expected given y is less complex by making every effort to be human friendly one.

Fig. 10 compares orbits between exponential function, logistic (epidemic) function and Lotka-Volterra function (see Section 2.2).[6] Under the foregoing condition that y is less complex and extremely human friendly one, Lotka-Volterra orbit could display concave and higher growth rate at the initial stage. Given the less complex innovation, this can be possible because of the maturity of growth condition, and due not only to the substitution proceeds for existing competitive species (x) under pure competition without any institutional constraints, but also to customer realizes potential benefit of y. This is quite similar to the diffusion orbit of transition from the cellular telephones to mobile Internet access service as reviewed in Section 2.1.3 (see Fig. 3).

As analyzed in Fig. 10, contrary to the logistic growth orbit, Lotka-Volterra orbit encompasses a possible orbit with higher dependency on new technology which substitutes for old one from the early stage of its introduction. As reviewed in Sections 1 and 3, given the slightly more 'successful species' existence, Lotka-Volterra orbit represents substitution and diffusion orbit under the conditions of pure competition between competing species just by functions of respective species with fair information, without fear of substitution, a reluctance to pay the cost of switching, and barriers within the manufacturing industry.

Therefore, for the acceleration of the diffusion process, factors separating the two orbits, logistic growth orbit and Lotka-Volterra orbit, should be removed. In order to lead Lotka-

[6] See Refs. [21–25] for comparison of diffusion orbit.

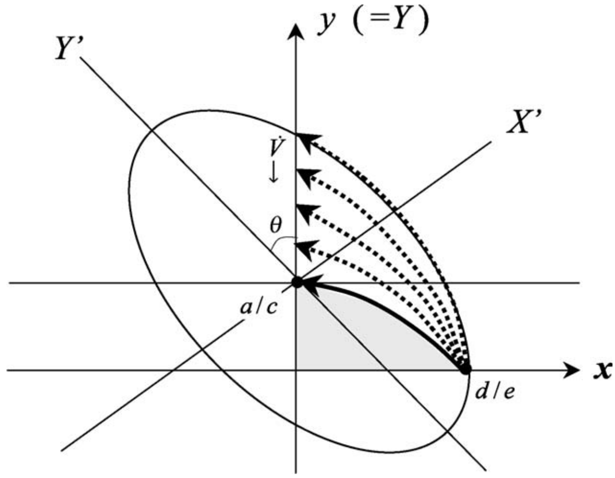

Fig. 8. General image of an elliptical orbit for substitution.

Volterra orbit to such expected orbit, every efforts to enhance the following three factors governing the orbit y such as, d (maximum diffusion scale), k_y (carrying capacity), and α_{yx} (interaction coefficient) in Eq. (1′) should be focused.

(1) Maximum diffusion scale: d.

d indicates the maximum diffusion of innovative goods in the market. Since the actual diffusion of innovative goods greatly depends on the elasticity of the potential users, it is crucial to take measures to stimulate the elastic reaction of the potential users to the innovative goods in order to accelerate the diffusion process.

From users' point of view, major factors that prevent them from adopting or switching to new technology are a lack of information about the innovation, that is, they do not know what

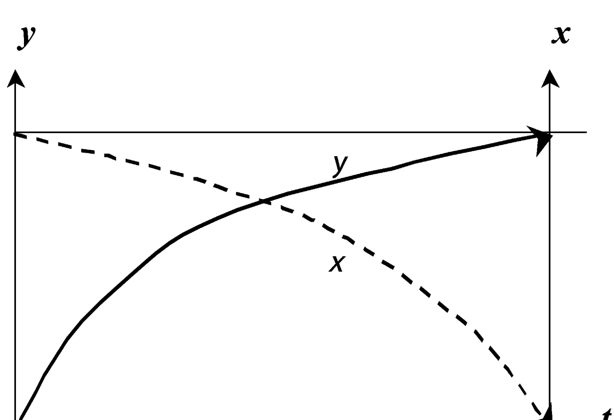

Fig. 9. Trend in x and y under y substitutes for x condition. x and y indicate the diffusion ratio.

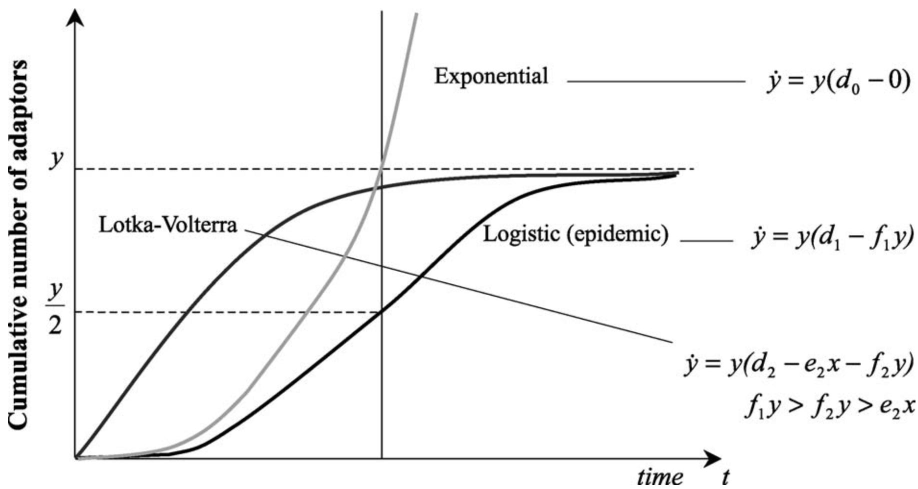

Fig. 10. Comparison between exponential function, logistic function and Lotka-Volterra function.

it is and how to use it, as well as a reluctance to pay the cost of switching. In this sense, efforts by supply side of the innovation such as intensive advertising for publicizing the merits of the innovation, providing user friendly interface, and public education are considered as very effective to push reluctant users to adopt the innovation spontaneously.

(2) Carrying capacity: k_y.

k_y indicates the ultimate upper limit (carrying capacity) of the adoptions of innovative goods. As Watanabe et al. [26] verified by analyzing the diffusion process of cellular telephones in Japan, since the diffusion process of the innovation which creates new functions during the course of its interaction with users can be well modeled by logistic growth within a dynamic carrying capacity, the potential of k_y can be regarded as much depending on the potential of the innovation towards multifunctionality.

There are mainly two factors to achieve multifunctionality: one is the R&D efforts by suppliers of the innovation and the other is the network externality of the innovation together with the elasticity of the market. It is rather obvious that new innovation obtained from the R&D efforts by suppliers have the possibility to add additional or completely new functionality to the original innovation, leading to achieving multifunctionality.

The other factor depends on the nature of the innovation. If the innovation has a feature of network externality, that is, if the innovation possesses a feature that the more it is deployed, the greater its value to the adopters, it has the potential to attract more and more users as well as other industries, assuming that the market is elastic enough to adopt the innovation. Broader interaction with users and other industries stimulate adding new functionalities to the original innovation.

(3) Interaction coefficient: α_{yx}.

α_{yx} indicates the intensity of competition between the existing goods (x) in the market and newly entering innovative goods (y). The value differs depending on the relationship between the two innovative goods: complementary, substitute, or fully competitive.

When the relationship is *complementary*, *y*'s diffusion proceeds rather quickly if *x* has already established some market share. Since *y* enhances the value of *x*, the diffusion of *x* and *y* is expected to grow mutually. When *y* substitutes *x*, it means that y's invasion power into *x* territory is stronger than that of *x* into *y*.

5. Conclusion

In light of the increasing significance of timely introduction of emerging new technologies that substitute for existing technology for enhancing a nation's international competitiveness in a globalizing economy, this paper, focusing on Japan's transition from manufacturing technology to IT, analyzes substitution orbits of two competitive innovations.

Prompted by a sophisticated balance of the co-evolution process in an ecosystem, particularly of the complex interplay between competition and cooperation, an application of Lotka-Volterra equations that analyze these sophisticated balance in an ecosystem, is conducted for reviewing the substitution orbits of Japan's monochrome to color TV system, fixed telephones to cellular telephones, and cellular telephones to mobile Internet access service, and analog to digital TV broadcasting.

On the basis of the comparative assessment by using synthesized two dimensional Lotka-Volterra equations for substitution and general logistic growth equation, following findings are obtained:

(i) Lotka-Volterra equations for substitution are useful for identifying an optimal orbit of competitive innovations with complex orbit.
(ii) It is particularly useful for assessing policy options from the view point of effectiveness in controlling parameters for leading to expected orbit.
(iii) Under the global paradigm shift from an industrial society to an information society, given the government target to accomplish a rapid shift from traditional technology to new technology, particularly IT driven new technology within a limited period, shifting scenario should be accelerated in line with Lotka-Volterra orbit with optimal coefficients.
(iv) In order to accomplish this orbit, every efforts should be accelerated in removing factors separating the two orbits between logistic growth orbit and Lotka-Volterra orbit including:
  (a) A lack of information about new technologies expected to be substituted for traditional one,
  (b) Fear of substitution and a reluctances to pay the cost of switching from traditional to new technology, and
  (c) Barriers to prompt shift to new technology within producers, distributors and customers.
(v) In addition, in order to accelerate such shift with a higher pace of Lotka-Volterra orbit, with the understanding that IT's specific functionality is formed through dynamic interaction with institutional systems [27], efforts should be focused on maximizing IT's self-propagation behavior.

Considering that while hasty shift sometimes accomplishes nothing, delayed shift can result in a loss of national competitiveness, identification of the optimal diffusion and substitution orbit is essential, thus, the foregoing approach is very useful in identifying policy options for the diffusion orbit of competitive innovations with complex interplay.

Further mathematical attempts aiming at broader application of possible orbit for substitution, together with empirical analyses taking "success stories" in smooth substitution and rapid diffusion such as mobile Internet access service on factors, conditions and systems enabled them rapid substitution and diffusion are expected to be undertaken.

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