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Functionality development dynamism in a diffusion trajectory: A case of Japan's mobile phones development

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A B S T R A C T

While it is generally accepted that Information Technology (IT) has a self-propagating function which ensures that the more widespread its use, the greater its functionality, its emerging dynamism remains a black box.

This paper attempts to shed some light on this dynamism through utilizing monthly trend data for the number of Japan's mobile phone subscribers over the last 12 years. A bi-logistic growth model demonstrating the diffusion trajectory initiated by both generations of mobile phones was constructed, with the goal of identifying the increase in the functionality development in the transition from traditional mobile phones with a simple communication function (1st wave mobile phone) to mobile phones with an Internet protocol function (2nd wave mobile phone). Through an empirical analysis utilizing the bi-logistic growth model, it was determined that the 2nd wave mobile phone emerged at an earlier stage of diffusion trajectory than the 1st stage mobile phone, which enabled a sustainable functionality development in Japan's mobile phones over the decade.

Factors governing a dramatic decrease in mobile phones prices were analyzed, utilizing the result of the measurement of functionality development. This led to the discovery that while an increase in functionality development enhanced the price of mobile phones, this increase accelerated self-propagating diffusion, thereby enabling a dramatic reduction in prices through the effects of learning exercise and economies of scale.

Based on the foregoing findings, the driving forces of self-propagating functionality development were analyzed, and it was determined that effective utilization of potential resources in innovation (e.g., assimilation of spillover technology and learning effects) is the key driving forces behind self-propagating functionality development.

1. Introduction

Fixed phones have demonstrated steadily increase in Japan as a fundamental communication mean and their total number of subscribers reached to 61.8 million in 1996 as shown in Fig. 1.

However, the number of mobile phone subscribers have increased since 1991, and exceeded the number of subscribers in message exchange and fixed phones in 1998. Starting from simple communication function, triggered by i-mode service in February 1999, mobile phones with an Internet protocol service exceeded those of non-Internet protocol mobile phones in 2001.

Diffusion of mobile phones can be classified into three stages as summarized in Table 1.

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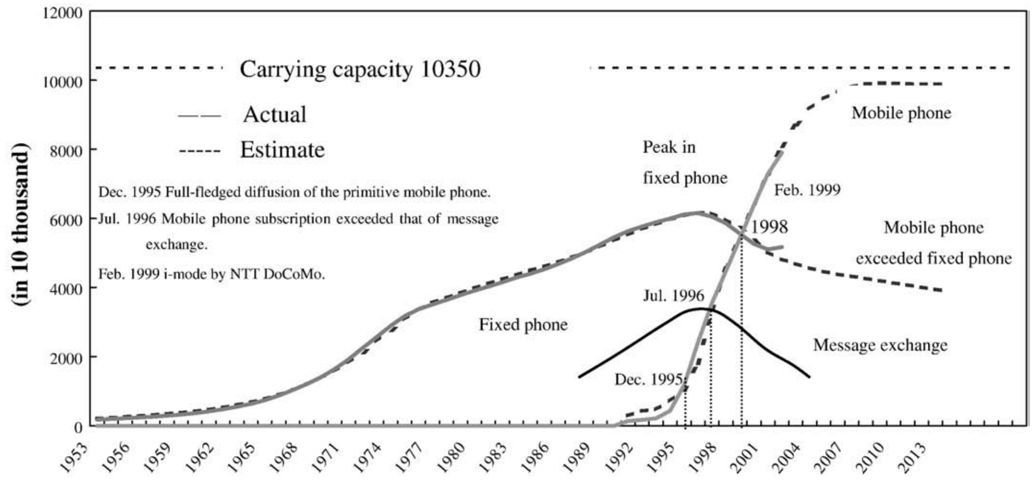


Fig. 1. Substitution trajectory of Japan's Japan's mobile phones for fixed line (1953–2006). a 1953–2004: Actual. b 2005–2015: Estimates by choice-based substitution diffusion model. Sources: Authors' Authors' elaboration based on Chen and Watanabe [1]. Original statistics are based on monthly reports by MIC, Japan [2].

In line with such dramatic diffusion, mobile phones have accomplished successive functionality development[1] – such as from talk to see, see and talk, listen, take a picture, pay and watch – as demonstrated in the self-propagating dynamism in functionality development in Japan's mobile phones development (see Fig. 2 in Section 2).

Incorporating such functionality development permits expensive handsets in mobile phones diffusion trajectory. At the same time, functionality development stimulates customer's demand leading to rapid increase in number of subscribers. This increase leads to dramatic decline in handsets prices as a result of both effects of learning and economies of scale. Balance between prices increase by functionality development and their decrease by effects of learning and economies of scale has been the driving force behind the growth in mobile phones.

Stimulated by these understandings, this paper attempts to analyze the functionality development dynamism in a diffusion trajectory.

Epidemic function has been popularly used for analyzing the diffusion trajectories in innovative goods [4]. This epidemic function identifies the contagion process similar to medical epidemic [5], and exhibits sigmoid growth. Since Verhulst introduced the logistic model depicting sigmoid growth in 1845, a number of studies have demonstrated the usefulness of this model in analyzing diffusion trajectory. A bi-logistic model postulated by Meyer [6] is utilized for a diffusion trajectory initiated by two co-existing innovations (e.g., two generations of mobile phones). It is generally postulated that growth patterns of successive innovations are sum of successive simple logistic models. In addition, the logistic growth function within a dynamic carrying capacity model [4] is utilized in estimating the diffusion trajectory of self-propagating dynamism [7]. The simple logistic growth function assumes that the level of carrying capacity is constant through the diffusion of innovation. However, in particular innovations, the level of carrying capacity will be enhanced as their diffusion proceeds [7]. Therefore, this model is introduced to trace self-propagating innovation process such as broad diffusion of IP mobile phones [1].

Watanabe et al. [7] postulated that the ratio of carrying capacity to the level of diffusion represents the extent of functionality development and this functionality development has become crucial for stimulating the self-propagating nature of IT-driven innovation. Furthermore, a dramatic deployment of mobile phones with new functionality can stimulate the self-propagating behavior of IT [7]. The emergence of innovation leads to functionality development and the efforts for maintaining the level of functionality development leads to create successive innovations.

In addition, functionality development is enhanced by the learning effect of the market in the long term. Following Arrow's postulate on “learning-by-doing” [8], Rosenberg [9] demonstrated “learning-by-using”, and then Cohen and Levinthal [10] stressed that cumulative learning stimulates assimilation of spillover technology. Moreover, Watanabe and Asgari [11] analyzed the dynamic interaction between learning effect and functionality development, and demonstrated that functionality development increases as learning increases leading to a virtuous cycle. The learning capacity increase leads to a price decrease as postulated by Arrow [8], and also the learning effects are generally considered as the correlation between a decrease in price and an increase in cumulative production. Therefore, a reduction in price through the learning effects and economies of scale is analyzed by elucidating the functionality development dynamism. Learning by doing refers to the process by which producers learn from experience. This process gives rise to increasing productivity over time and to ecomies of scale. Ecomomies of scale refers to the decreased per unit cost as outputs increase. In general, the initial investment of capital is diffused over an increasing number of units of output, and therefore, the marginal cost of producing a good or service decreases as production increases. The Boston

[1] The functionality development is generally defined as the ability to dramatically improve performance of production processes, goods and services by means of innovation [3].

Table 1
Development phases of Japan's mobile phone.

Development phase		Time of the emergence	Remark
Phase 0	Primitive mobile phones	Dec. 1995	Full-fledged diffusion of the primitive mobile phones
Phase 1	1st wave of mobile phones	Jul. 1996	Mobile phones subscription exceeded that of message exchange
Phase 2	2nd wave of mobile phones	Feb. 1999	i-mode by NTT DoCoMo

Consulting Group [12] argued that prices decline in most industries as learning proceeds. Lieberman [13], Gruber [14], Nye [15], and Siebert [16] demonstrated the relationship between effects of learning process and economies of scale.

To date, while a number of studies have attempted to analyze functionality development dynamism in the diffusion process, its mechanism has still remained a black box.

This paper, based on the empirical analysis of the diffusion trajectory of Japan's mobile phones development over the last decade and utilizing the bi-logistic growth function, first attempts to develop a numerical function depicting the trend in functionality development in successive innovations. Second, by incorporating this function into a price formation function, governing factors and their magnitude to increase and decrease in price of innovative goods is analyzed. Third, utilizing the result of the price formation analysis, inside the black box of the dynamism of the driving force of mobile phones development is elucidated. Fourth, based on these analyses, sources of self-propagating functionality development in firm's technopreneurial trajectory are identified.

Section 2 provides the analytical framework of numerical analysis. Section 3 presents an empirical analysis on the diffusion trajectory of Japan's mobile phones. Section 4 demonstrates the functionality development in a diffusion process. Section 5 identifies the factors contributing to the prices decrease in Japan's mobile phone handsets. Section 6 attempts further development for the identification of the sources of self-propagating functionality development. Section 7 briefly summarizes new findings, policy implications and focus of the future work.

2. Analytical framework

2.1. Functionality development in a diffusion process

Corresponding to the broad diffusion of mobile phones with an Internet protocol, functionality development in a self-propagating way has been clearly observed. This process can be traced by the logistic growth function within a dynamic carrying capacity. First, the following epidemic function with its carrying capacity N has been popularly used for analyzing the diffusion trajectories in innovative goods [4].

$$\frac{d}{dt}V(t) = aV(t)\left(1-\frac{V(t)}{N}\right) \tag{1}$$

$$V(t) = \frac{N}{1+be^{-at}} \tag{2}$$

where $V(t)$: cumulative number; N: carrying capacity; a: velocity of diffusion; b: initial stage of diffusion; and t: time trend.

This carrying capacity itself enhances in the diffusion process of mobile phones as $N(t)$ which can be traced also by the following epidemic function [1]:

$$\frac{d}{dt}N(t) = a_k N(t)\left(1-\frac{N(t)}{N_k}\right) \tag{3}$$

$$N(t) = \frac{N_k}{1+b_k e^{-a_k t}} \tag{4}$$

where N_k: ultimate carrying capacity; a_k: velocity of diffusion; and b_k: initial stage of diffusion.

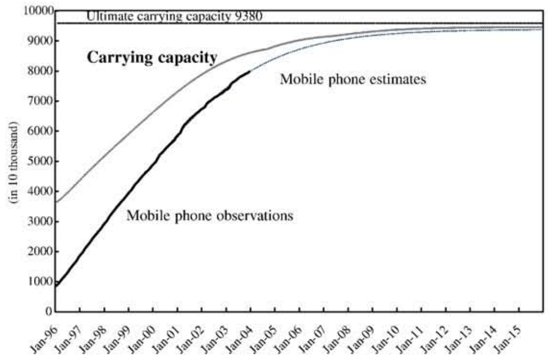
Synchronizing Eqs. (2) and (4), the following logistic growth function within a dynamic carrying capacity can be developed:

$$V(t) = \frac{N_k}{1+be^{-at}+\frac{b_k}{1-a_k/a}e^{-a_k}} \tag{5}$$

Diffusion trajectory of mobile phones can be estimated by this logistic growth function within a dynamic carrying capacity with self-propagating behavior in their diffusion process as demonstrated in Fig. 2.

Since the diffusion of IT is induced by the demand to functionality development, this demand terminates at $\mathrm{d}V/\mathrm{d}t = 0$ when $V(t)$ reaches to carrying capacity N. Therefore, the capacity of functionality development (FD) in the diffusion process can be measured by a ratio between carrying capacity and level of diffusion as $\mathrm{FD} = N/V(t)$. When the diffusion accesses to carrying capacity, functionality development exhausts leading to $\mathrm{d}V/\mathrm{d}t = 0$. Therefore, efforts for prolongation of the functionality development lead

Parameter	Estimate	t-value	*adj.* R^2
a	1.48 10^{-1}	8.94	0.998
b	1.44 10^{2}	9.85	
a_k	3.43 10^{-2}	7.63	
b_k	4.21 10^{0}	8.65	
N_k	9.38 10^{3}	10.89	



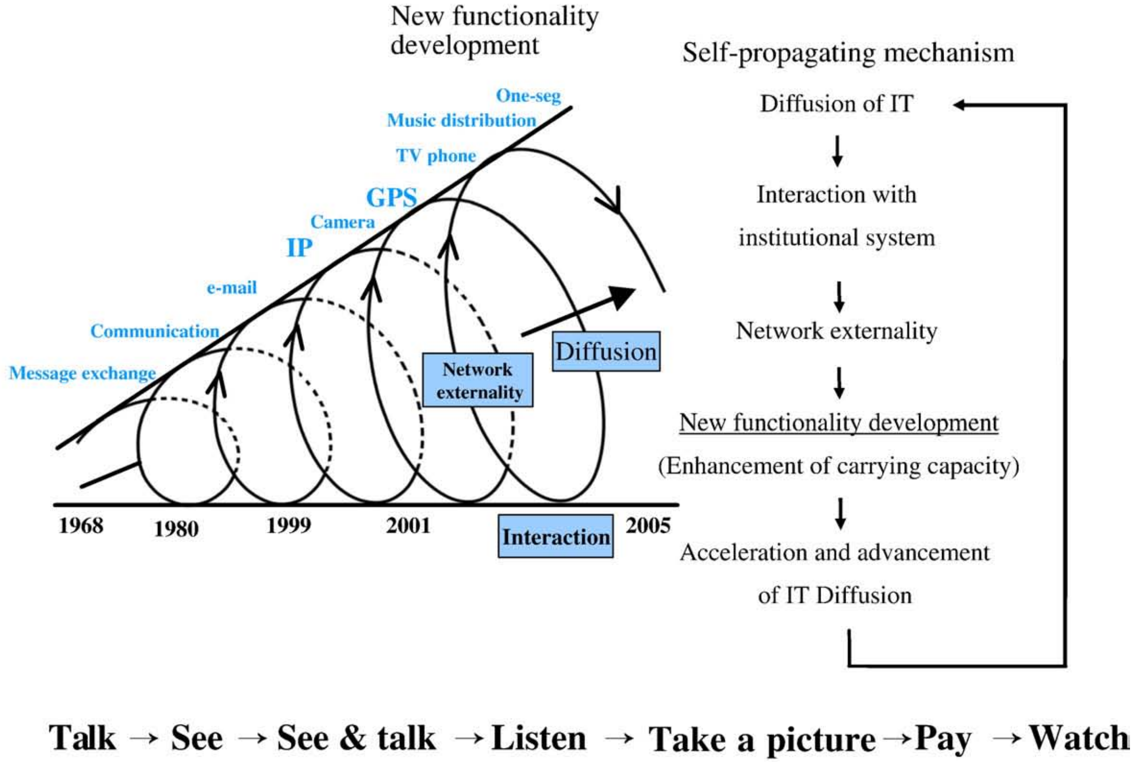


Fig. 2. Self-propagating dynamism in new functionality development in Japan's Japan's mobile phones development. a Estimation of the logistic growth function within a dynamic carrying capacity is conducted by means of monthly data over the period Jan. 1996–Dec. 2003.

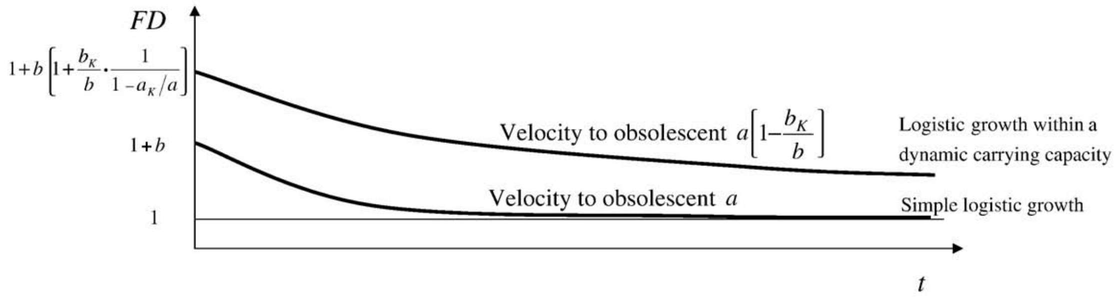


Fig. 3. The obsolescence and prolongation of functionality development.

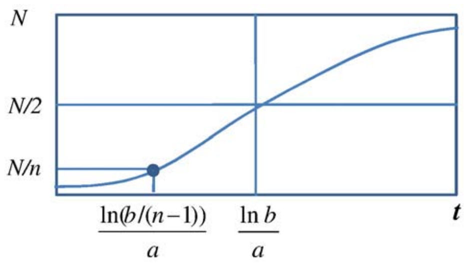


Fig. 4. Diffusion level emerging functionality development and its timing.

to logistic growth function within a dynamic carrying capacity that enhances carrying capacity as diffusion proceeds. In this case, functionality development (FD) can be depicted as follows:[2]

$$\mathrm{FD} = \frac{N_k}{V} = 1 + b\left(1 + \frac{b_k}{b}\cdot\frac{1}{1 - a/a_k}\right)e^{-a\left(1-\frac{b_k}{b}\right)t} \tag{6}$$

Fig. 3 demonstrates the obsolescence and prolongation effort to functionality development in the diffusion trajectory in the logistic growth function within a dynamic carrying capacity.

As demonstrated in Fig. 3, since $b\left(1 + \frac{b_K}{b}\cdot\frac{1}{1 - a_K/a}\right) > b, a\left(1 - \frac{b_K}{b}\right) < a$ and initial level of functionality development increases and velocity to obsolescent decreases as b_K/b increases. Thus, b_K/b demonstrates "prolongation ability."

2.2. Functionality development dynamism

Functionality development (FD) emerges in the market when diffusion reaches certain level and customers share information sufficient enough to eliminate fear of new innovation. Provided that this level is equivalent to one nth of the ultimate diffusion level (N), this can be enumerated as $N/\mathbf{n}$ and the time to reach this level can be identified as $\frac{\ln(b/(n-1))}{a}$ as illustrated in Fig. 4. Level of functionality development at this time equivalent to its emergence is n.

Given this level is $N/2$, this timing can be identified as $\frac{\ln b}{a}$. Thus, given the two co-existing innovation diffusion V_1 and V_2 as depicted by the following bi-logistic growth model, levels of diffusion and functionality development as well as the time when each respective functionality development emerges can be identified as summarized in Table 2 and illustrated in the upper part of Fig. 5.

$$V = V_1 + V_2 = \frac{N_1}{1 + b_1 e^{-a_1 t}} + \frac{N_2}{1 + b_2 e^{-a_2 t}} \tag{7}$$

where N_1 and N_2: carrying capacities; a_1 and a_2: velocity of diffusion; b_1 and b_2: initial stage of diffusion; and t: time trend.

Since the functionality development is the ratio of carrying capacity (N) and the level of diffusion, functionality development level at its initial emergence can be identified as $n_1\left(=\frac{N_1}{N_1/n_1}\right)$ and $n_2\left(=\frac{N_2}{N_2/n_2}\right)$, respectively as also indicated in Table 2 and the lower part of Fig. 5.

In order to win the race in a competitive market, firms endeavor to develop new innovation which incorporates higher functionality development leading to the successive innovation as series of mobile phones development. Functionality development level in each individual innovation V_i declines in a logistic way as time goes with its maximum level at its initial emergence of $\boldsymbol{n_i}$. Provided that firms endeavor to develop higher innovation V_{i+1}, its maximum functionality development level $\boldsymbol{n_{i+1}}$ is higher than

[2] See detail in Appendix A-1.

Table 2
Estimation of the levels of diffusion and *FD* as well as the time in its emergence.

Development phase	Level of diffusion	Timing	*FD*
V_1	$N_1\ /n_1$	$t_1 = \frac{ln(b_1\,/\,(n_1-1))}{a_1}$	N_1
V_2	$N_2\ /n_2$	$t_2 = \frac{ln(b_2\,/\,(n_2-1))}{a_2}$	n_2

preceding one. Thus, customers prefer to shift from $\boldsymbol{n_i}$ to $\mathbf{n_{i+1}}$ rather than cling to the traditional functionality development developed by V_i that inevitably decreases. Consequently, trajectory of functionality development on which customers depend ($\overline{\mathrm{FD}}$Z) is an envelope curve with a function of $\boldsymbol{n_i}$ ($\mathrm{FD_{env.}}(n_i)$) as depicted by the following functions and illustrated in the lower part of Fig. 5 (see predictive power of this model in Appendix B).

$$\overline{\mathrm{FD}} = \mathrm{FD_{env.}}(n_i), \quad n_i = \mathrm{FD}_i(t_i) = 1 + b_i e^{-a_i t_i}, \quad t_i = ln(b_i\,/\,(n_i-1))\,/\,a_i \tag{8}$$

3. Diffusion trajectory of Japan's mobile phones

In line with the analytical framework in the preceding section, aiming at analyzing the dynamism of the functionality development trajectory of the successive innovation in Japan's mobile phones development, an empirical analysis by utilizing the bi-logistic growth model as depicted in Eq. (7) and utilizing monthly data on the number of mobile phone subscribers over the period December 1995–December 2006 is conducted. The result of the analysis is summarized in Table 3.

Table 3 demonstrates that all parameters prove statistically significant. Comparing two waves, V_1 and V_2, we note that the second wave diffuses with lower rate of obsolescence than the first wave (a_2 is one half of a_1) leading to higher level of carrying capacity (N_2 is 2 times higher than N_1). In order to examine the self-propagating dynamism in a diffusion trajectory, the sequential diffusion of functionality development in the mobile phone is analyzed by means of the bi-logistic growth model. Utilizing the estimated bi-logistic growth model, monthly diffusion trajectory of Japan's mobile phones over the period December 1995–December 2006 is decomposed into two waves, mobile phones without an Internet protocol function and those with an Internet protocol function as illustrated in the top figure in Fig. 6. Aiming at identifying the point of the emergence of the functionality development and also the timing of the transition to the new functionality development, based on the review of the level and

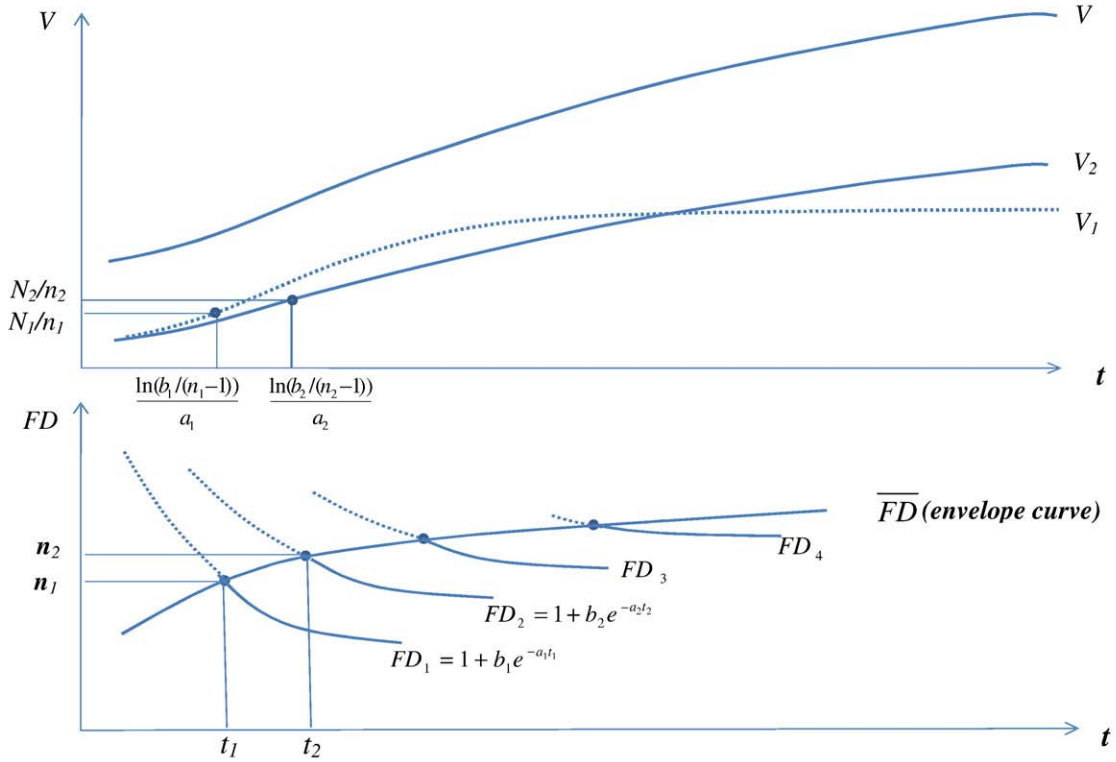


Fig. 5. Scheme of functionality development corresponding to the diffusion of the successive innovation.

Table 3
Estimation of Japan's mobile phones diffusion by the bi-logistic growth (December 1995–December 2006).

	N_1	a_1	b_1	N_2	a_2	b_2	adj. R^2
Parameter	35.147	0.074	5.198	65.418	0.036	14.028	0.999
t-value	2.25*	4.59*	3.26*	3.81*	6.74*	1.33**	

* Indicates significant at the 1% level.
** Indicates significant at the 10% level.

timing of inflection in diffusion trajectory (see Appendix B), the first and second derivative of the diffusion trajectory of two waves are analyzed as demonstrated in the middle and the lower parts in Fig. 6.

Following Rogers' pioneer work on the innovativeness based on adopter of the categorization [17], Mahajan et al. [18] pointed out the functionality development emerged in the market at transition from early adopters to late adopters[3]. This timing corresponds to the timing $\frac{ln(2-\sqrt{3})b}{a}$. In addition, functionality development stagnates at the transition from late majority to laggards corresponding to the timing $\frac{ln(2+\sqrt{3})b}{a}$ (see Fig. A1 in the Appendix B).

The first and the second derivative of two waves of Japan's mobile phones diffusion as demonstrated in Fig. 6 indicate these critical points as summarized in Table 4.

Fig. 7 reviews the chronology of the development paths of Japan's mobile phones in both the first wave and the second wave and also suggests the major critical steps of these developments as summarized in Table 5.

Comparing Tables 4 and 5, we note the following important findings:

(i) Functionality development of the 1st wave of mobile phones emerged in July 1996 corresponding to $\frac{ln(2-\sqrt{3})b_1}{a_1}$.
(ii) The first wave of mobile phones stagnated from April 1999 corresponding to $\frac{ln(2+\sqrt{3})b_1}{a_1}$ and transferred to the second mobile phones corresponding to $\frac{ln(2-\sqrt{3})b_2}{a_2}$ of its diffusion.
(iii) Functionality development of the 2nd mobile phones emerged in February 1999, 2 months earlier than the timing of inflection points $\frac{ln(2+\sqrt{3})b_2}{a_2}$.

On the basis of the foregoing observations, Fig. 8 illustrates functionality development trajectory of the successive innovations in Japan's mobile phones. This Figure demonstrates the level of functionality development in the 1st mobile phones which emerged in July 1996 as $3+\sqrt{3}$. This level increases to 5.0 in functionality development of the 2nd mobile phones which emerged in February 1999 (see Appendix A-2).

4. Functionality development in a diffusion process

Functionality development (FD) increases as time t increases with diminishing returns to scale with respect to t as depicted by the following equation:

$$\frac{d\mathrm{FD}}{dt} = H \cdot t^{\mu} \tag{9}$$

Integrating by time t leads to the following equation:

$$\mathrm{FD} = \frac{H}{\mu+1} t^{\mu+1} + C \tag{10}$$

where H ($H>0$): scale factor; μ ($\mu<0$): coefficient; and C: integral constant ($=FD_{t=0}$).

$FD_{t=0}$ indicates functionality development level at the time of the emergence of Japan's primitive mobile phones and they can be identified as December 1995 with the functionality development level of 3.838 (see details in Appendix C). Given that $t=0$ at this timing December 1995, emergences of the 1st and 2nd mobile phones are at $t=7$ (July 1996) with the functionality development level of $3+\sqrt{3}$, and $t=38$ (February 1999) with the functionality development level of 5, respectively. Utilizing the foregoing three sets of empirical data, the value of H and μ are estimated 0.048 and -0.330, respectively. On the basis of this estimation, functionality development can be expressed as follows:

$$\mathrm{FD} = 0.072t^{0.670} + 3.838 \tag{11}$$

Consequently, functionality development trajectory as demonstrated in Fig. 9 can maintain sustainable increase in functionality development.

[3] Mahajan et al. [18] pointed out that adopters who adopt earlier than others are likely to have more gain from the use of the product and hence have a greater usage propensity, and additionally adoption of complex products such as personal computers depend on buyers' ability to develop new knowledge and new patterns of experience.

5. Factors contributing to the prices decrease

Fig. 10 demonstrates the trend in prices of Japan's mobile phone handsets over the period January 2000–December 2006.

Looking at Fig. 10 we note that while Japan's mobile phone handsets prices continued to decrease with 12 ~ 14% per month decreasing rate, this rate stagnated to 9% per month after the beginning of 2005. Factors governing these trends can be considered as the effects of functionality development, learning exercise and economies of scale. Moore's law describes that the number of transistors double every 18 months [20]. Stimulated by this Moore's law, Jovanovic and Rousseau [21] demonstrated that link Moore's law with learning by doing and analyzed relationship between price and cumulative output by utilizing learning curve. Prompted by these understandings, the factors contributing to the prices decrease in Japan's mobile phones are analyzed.

While functionality stimulates customer's demand leading to a rapid increase in number of subscribers, this increase induces both effects of learning and economies of scale leading to dramatic decline in handsets prices.

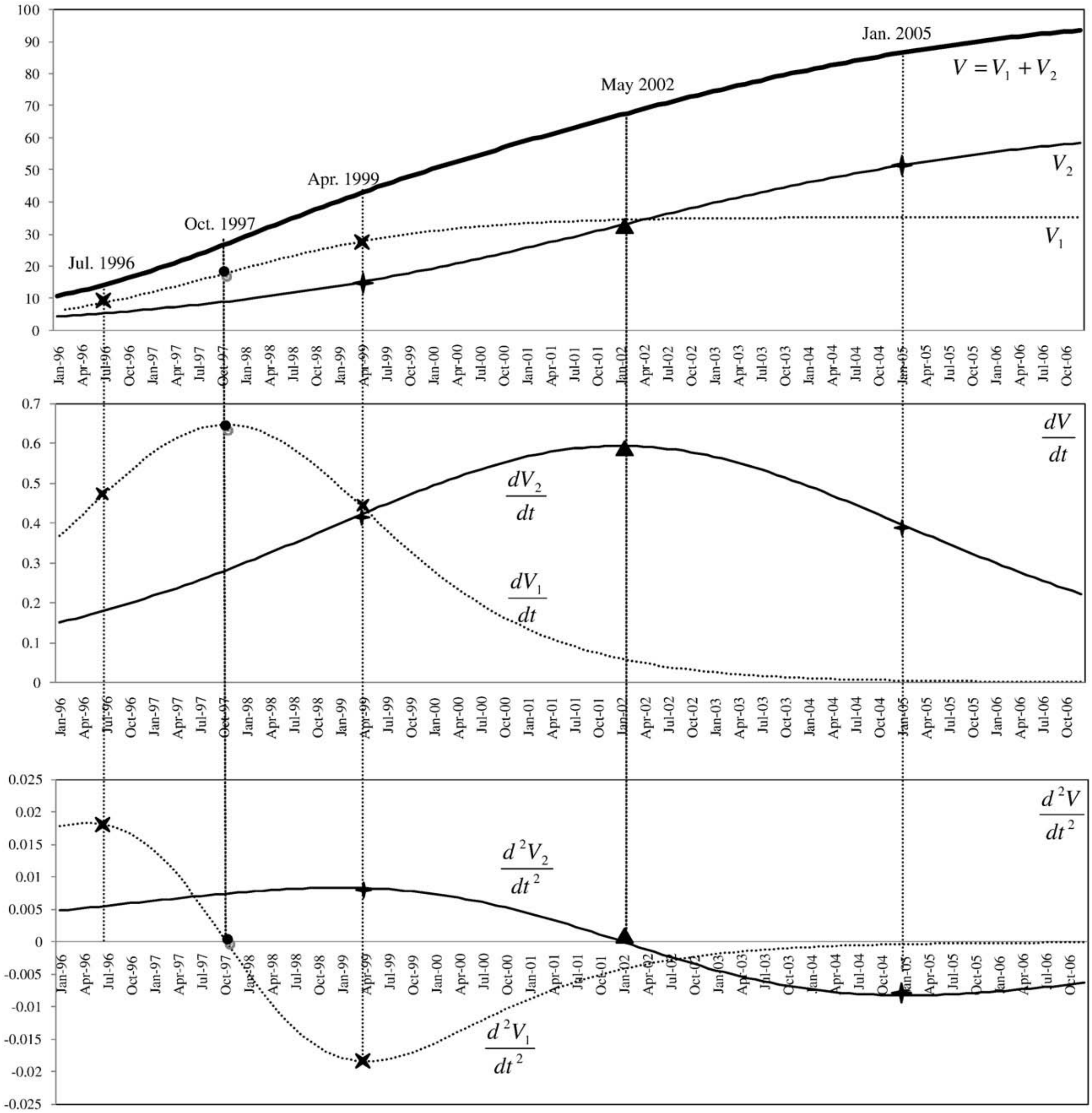


Fig. 6. Diffusion dynamism of Japan's Japan's mobile phones (December 1995–December 2006).

Table 4
Inflection points of two waves in Japan's mobile phones diffusion (December 1995–December 2006).

	Inflection points	
	$t_1 = \frac{ln\left(2-\sqrt{3}\right)b}{a}$	$t_2 = \frac{ln\left(2+\sqrt{3}\right)b}{a}$
First wave (Mobile phones without Internet protocol)	Jul. 1996 ($t=7$)	Apr. 1999 ($t=40$)
Second wave (Mobile phones with Internet protocol)	Apr. 1999 ($t=40$)	Jan. 2005 ($t=109$)

Thus, factors governing the prices of Japan's mobile phone handsets can be depicted by the following function:

$$P = A \cdot \mathrm{FD}^{\alpha} \cdot V^{\beta} \cdot e^{\gamma t + \delta D} \tag{12}$$

$$lnP = lnA + \alpha ln\mathrm{FD} + \beta lnV + \gamma t + \delta D \tag{13}$$

where P: prices of mobile phones handsets (2000 = 100); A: scale factor; FD: functionality development; V: a number of subscribers; t: monthly time trend; D: dummy variable corresponding to the changes in external circumstances; and α, β, γ, and δ: coefficients.

By means of the regression analysis, parameters in Eq. (13) can be identified as follows:

$$lnP = \underset{(-6.58)}{-718.181} + \underset{(6.65)}{589.339}\, ln\mathrm{FD} - \underset{(-6.73)}{39.199}\, lnV - \underset{(-6.72)}{0.606}t + \underset{(12.55)}{0.031}D_1$$

Based on this result, factors contributing to change in prices can be identified as summarized in Table 6 and Fig. 11.

Fig. 11 demonstrates that successive functionality development increase contributed to prices increase while subsequent effects of learning and economies of scale contributed to prices decrease. As a consequence of the balance between these increase and

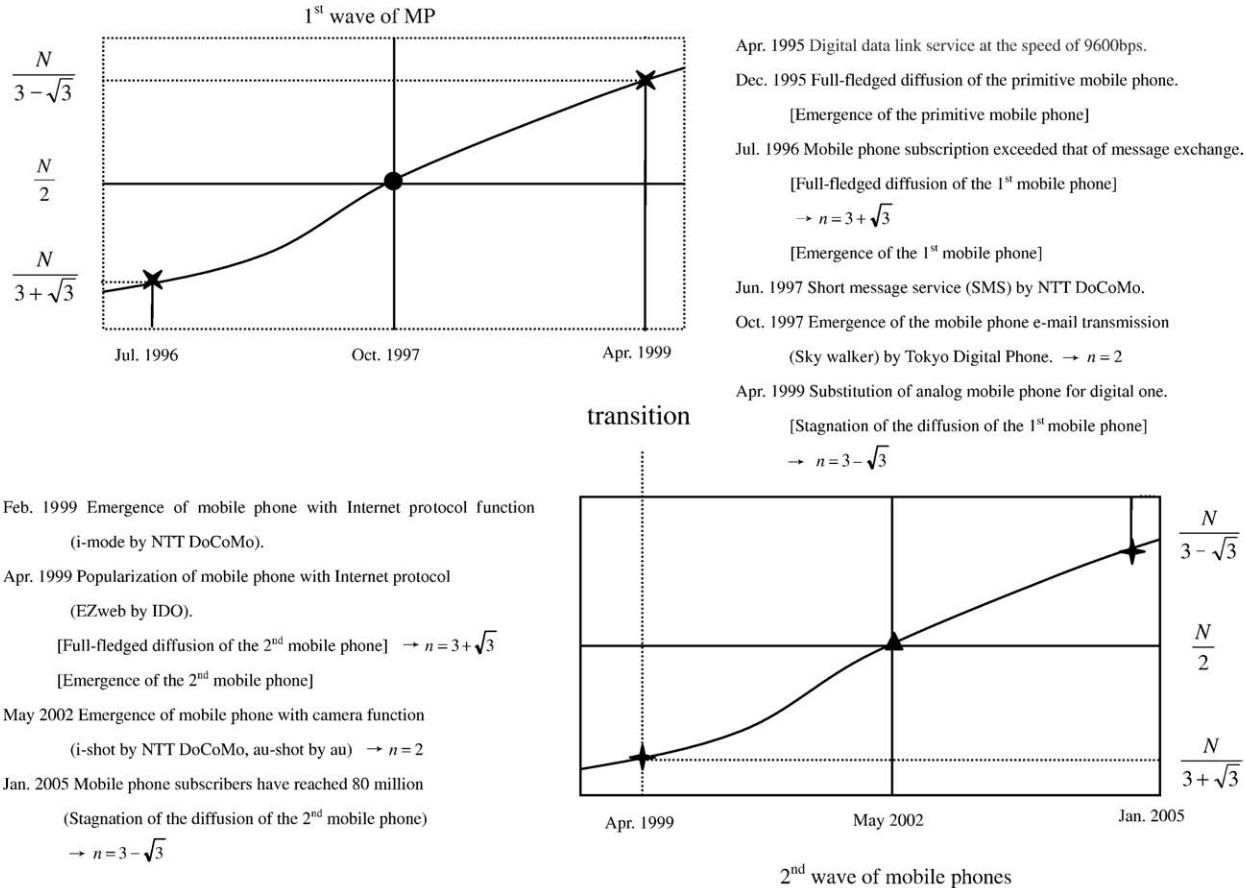


Fig. 7. Diffusion and transition of the 1st and 2nd waves of Japan's Japan's mobile phones.

Table 5
Critical steps of development of two waves of mobile phones in Japan.

Period	Steps of development
1st wave	
Jul. 1996	Mobile phone subscription exceeded that of message exchange. [This is equivalent to full-fledged diffusion of the 1st mobile phone and emergence of it]
Oct. 1997	Emergence of the mobile phone e-mail transmission (Sky walker) by Tokyo Digital Phone.
Apr. 1999	Substitution of analog mobile phone for digital mobile phone. [This is equivalent to stagnation of the diffusion of the 1st mobile phone]
2nd wave	
Feb. 1999	Emergence of mobile phone with IP function (i-mode by NTT DoCoMo). [This is equivalent to emergence of the 2nd mobile phone]
Apr. 1999	Popularization of mobile phone with Internet protocol function (EZweb by IDO). [This is equivalent to full-fledged diffusion of the 2nd mobile phone]
May 2002	Emergence of protocol with camera function (i-shot by NTT DoCoMo, and au-shot by au)
Jan. 2005	Mobile phone subscribers have reached 80 million. [This is equivalent to stagnation of the diffusion of the 2nd mobile phone]

decrease, price of the handsets have maintained decreasing trend and this balance can be crucial driving forces of mobile phone growth as illustrated in Fig. 12.

Balance between increase in prices by functionality development and their decrease in prices by effects of learning and economies of scale induce the driving force of mobile phones development.

6. Sources of self-propagating functionality development

Since high technology products can be considered as the crystal of technology stock, the epidemic function can be developed incorporating technology stock T[4] instead of time t as follows [22]:

$$V(t) = \frac{N}{1 + be^{-aT}} \tag{14}$$

Since $a \ll 1$[5],

$$\mathrm{FD} = \frac{N}{V(t)} = 1 + be^{-aT} \approx 1 + b(1 - aT) \tag{15}$$

Taking partial differentiation of Eq. (14) with respect to technology stock T, the following equation depicting marginal productivity of technology can be obtained:

$$\begin{aligned} \frac{\partial V}{\partial T} &= aV\left(1 - \frac{V}{N}\right) \\ &= aV\left(1 - \frac{1}{\mathrm{FD}}\right) \end{aligned} \tag{16}$$

where $\mathrm{FD} \equiv N/V$: degree of functionality development [3].

Technology stock T consists of indigenous technology stock T_i and assimilated spillover technology zT_s as follows:

$$T = T_i + zT_s \tag{17}$$

where T_s: technology spillover pool; and z: assimilation capacity (see detail in Appendix A-3).

Therefore, FD in Eq. (17) can be developed as follows (see detail in Appendix A-4):

$$\begin{aligned} \mathrm{FD} &= 1 + b(1 - a(T_i + zT_s)) \\ &\approx \left(1 + b_1 e^{-a_1 T_i}\right) + \left(1 + b_2 e^{-a_2 z T_s}\right) \end{aligned} \tag{18}$$

where $a_1 \equiv \left(\frac{ab}{(b-1)p}\right), \quad a_2 \equiv \left(\frac{ab}{(b-1)q}\right), \quad b_1 \equiv (b-1)p, \quad b_2 \equiv (b-1)q$ and $p + q = 1$.

This is equivalent to the successive FDs (FD_1 and FD_2) generated by the bi-logistic growth model as:

$$V = V_1 + V_2 = \frac{N_1}{1 + b_1 e^{-a_1 T_i}} + \frac{N_2}{1 + b_2 e^{-a_2 z T_s}} \tag{19}$$

where V_1: 1st wave generated by indigenous technology stock T_i; and V_2: 2nd wave generated by assimilated by spillover technology zT_s.

[4] Technology stock implies technological knowledge stock generated by R&D investment, postulated by Griliches [23] and Watanabe [24], this stock can be measured by the following equation:

$$T_t = R_{t-m} + (1 - \rho)T_{t-1}$$

where T_t: technology stock at time t; R_t: R&D investment at time t; m: lead time between R&D and commercialization; and ρ: rate of obsolescence of technology.

[5] Table 3 demonstrates that the values of a for the first and second wave of MP are 0.074 and 0.036, respectively.

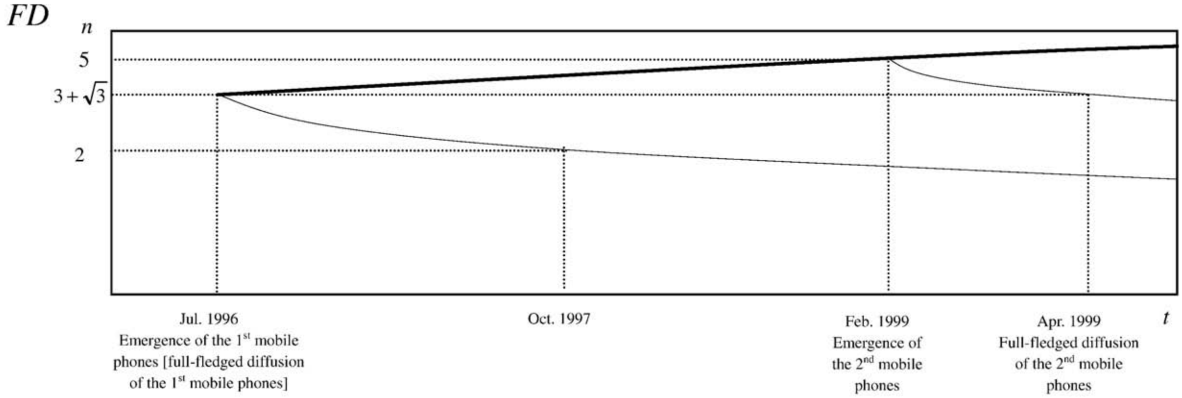


Fig. 8. Functionality development trajectory of the successive innovation in Japan's mobile phones.

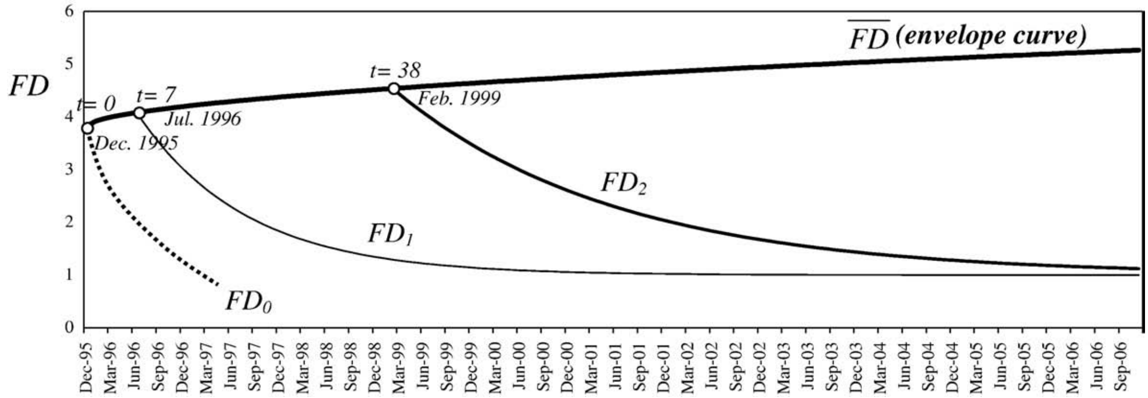


Fig. 9. Trajectory of functionality development in Japan's mobile phones (1995–2006).

Therefore, functionality development generated by assimilating spillover technology is equivalent to those generated by the bi-logistic growth model with V_1 and V_2.

This suggests that assimilating spillover technology is essential for self-propagating functionality development in firm's technopreneurial trajectory.

7. Conclusion

In light of the significance of the sustainable functionality development for firms' competitiveness in an information society, functionality development dynamism in a diffusion trajectory was investigated. In this paper, the diffusion trajectories from mobile

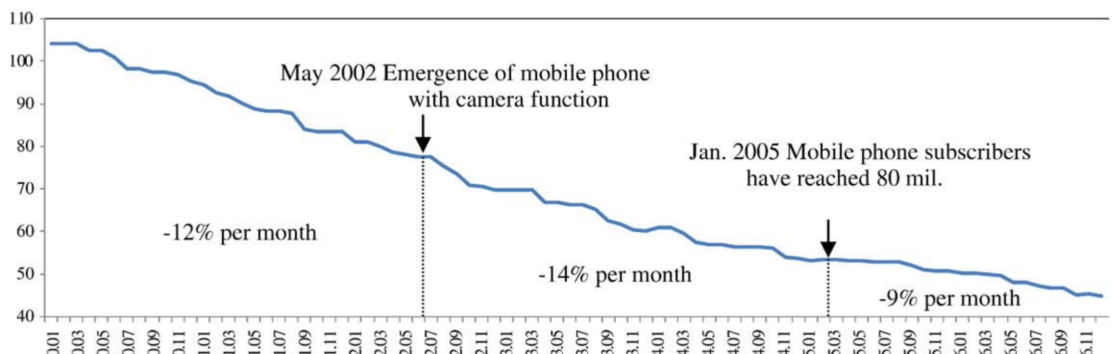


Fig. 10. Trend in prices of Japan's Japan's mobile phone handsets (January 2000–December 2006) — Index of production prices by 2000 fixed price: year 2000 = 100. Source: Bank of Japan (annual issues) [19].

Table 6
Factors contributing to change in prices of Japan's mobile phones handset (January 2000–December 2006).

	P	FD	*V*	Time	Residual
Jan. 2000–May 2002	−0.12	12.90	−6.07	−7.26	0.32
May 2002–Jan. 2005	−0.14	10.37	−3.26	−7.26	0.02
Jan. 2005–Dec. 2006	−0.09	10.30	−1.74	−7.26	−1.39

phones with a simple communication function to mobile phones with an Internet protocol function was first examined for the measurement of the functionality development, using monthly trend data for the number of Japan's mobile phones subscribers over the last 12 years. Factors governing a dramatic decrease in mobile phones prices were analyzed, utilizing the result of the measurement of functionality development. In addition, based on this analysis, the driving forces behind self-propagating functionality development were analyzed. These analyses led to identification of the sources enabling self-propagating functionality development in firm's technopreneurial trajectory.

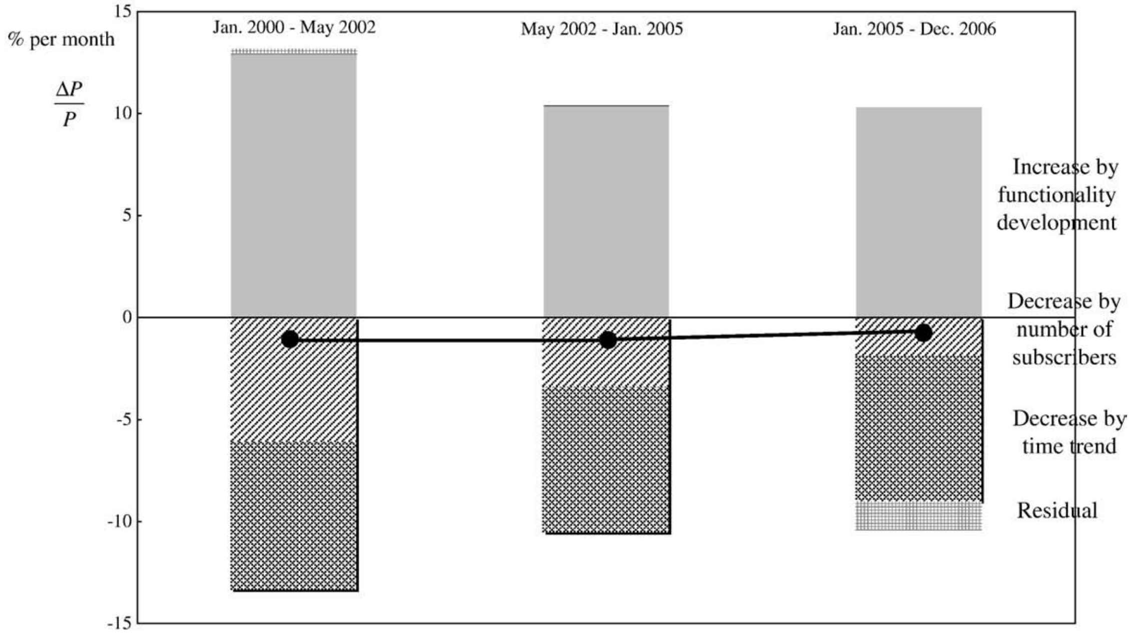


Fig. 11. Trends in factors and their magnitude contributing to change in prices of Japan's Japan's mobile phone handset (January 2000–December 2006).

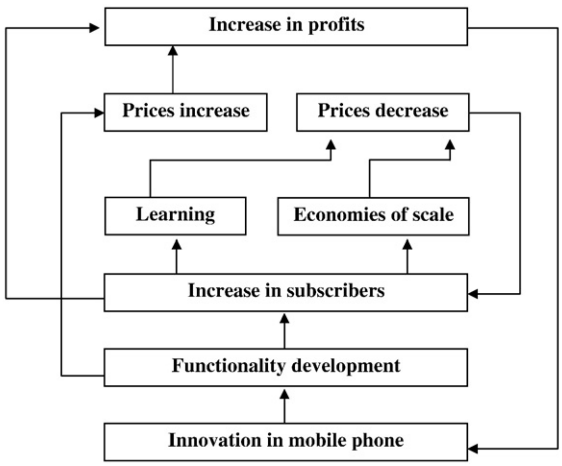


Fig. 12. Dynamism of the driving forces of developing mobile phones growth.

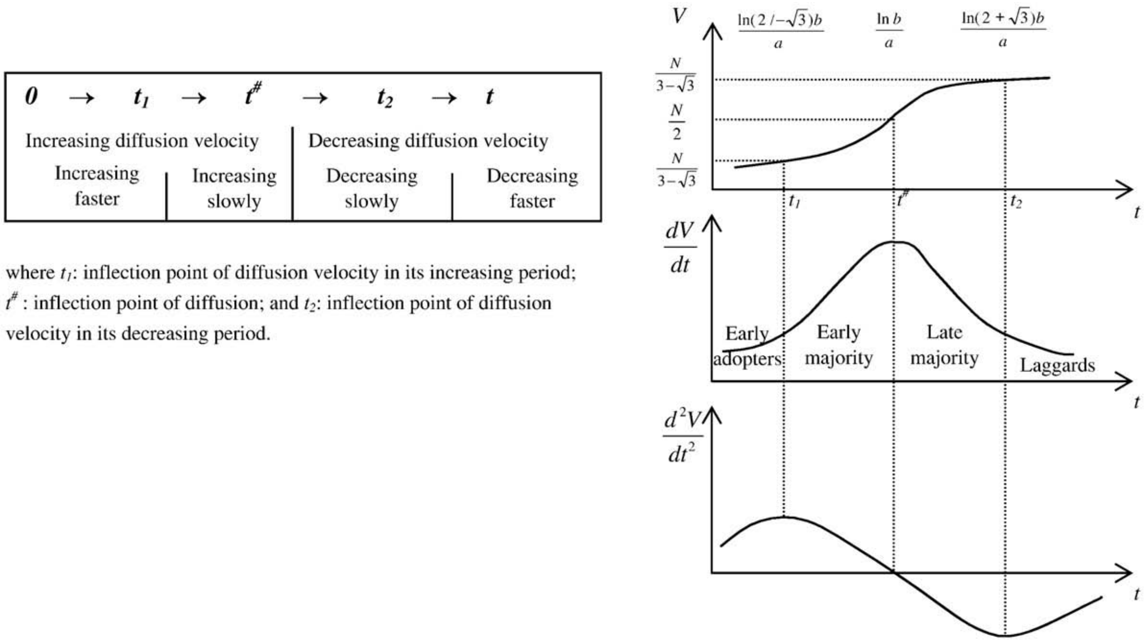


Fig. A1. Level and timing of inflection in diffusion trajectory.

Noteworthy findings obtained include:

(i) It was determined that mobile phones with an Internet protocol function emerged at an earlier stage of diffusion trajectory than traditional mobile phones with a simple communication function,
(ii) This has enabled a sustainable functionality development in Japan's mobile phones over the decade,
(iii) It was found that while an increase in functionality development enhanced the prices of mobile phones, this increase accelerated self-propagating diffusion enabling a dramatic reduction in prices through the effects of learning exercise and economies of scale, and
(iv) Effective utilization of potential resources in innovation (e.g. assimilation of spillover technology and learning effects) is the key driving forces behind self-propagating functionality development.

These findings suggest the following policy implications suggestive to sustainable functionality development for firms for their competitiveness increase:

(i) Earlier undertaking of the new innovation than the preceding one is essential for self-propagating functionality development,
(ii) Virtuous cycle between functionality development and acceleration of the self-propagating diffusion is essential for gaining profit while decreasing prices,
(iii) Effective utilization of potential resources in innovation is essential for self-propagating functionality development, and
(iv) Effective learning and assimilation of spillover technology are thus important for firm's technopreneurial trajectory management.

Further works should focus on the in-depth analysis taking institutional factors into the foregoing analyses thereby identify the similarity and disparity of the functionality development dynamism between countries with different institutional systems.

Appendix A. Math derivations

Appendix A-1

Eq. (5) can be approximated as follows:

$$V = \frac{N_K}{1 + be^{-at} + \frac{b_K}{1 - a_K/a}e^{-a_K t}} = \frac{N_K}{1 + be^{-at}\cdot\left(1 + \frac{b_K}{b}\cdot\frac{1}{1 - a_K/a}e^{(a - a_K)t}\right)} \approx \frac{N_K}{1 + be^{-at}\cdot e^{\frac{b_K}{b}\cdot\frac{1}{1 - a_K/a}(1 + (a - a_K)t)}} \approx \frac{N_K}{1 + be^{\frac{b_K}{b}\cdot\frac{1}{1 - a_K/a}}\cdot e^{-a\left(1 - \frac{b_K}{b}\right)t}}$$
$$\approx \frac{N_K}{1 + b\left(1 + \frac{b_K}{b}\cdot\frac{1}{1 - a_K/a}\right)\cdot e^{-a\left(1 - \frac{b_K}{b}\right)t}}$$

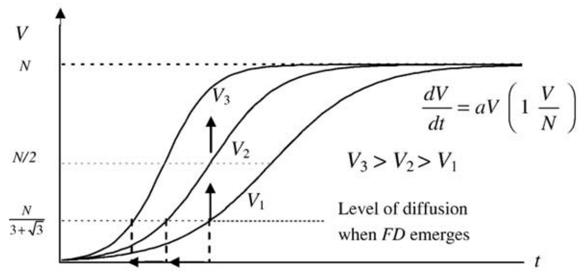


Fig. A2. Diffusion trajectory and functionality development of innovation.

Appendix A-2

The level of functionality development in the 2nd mobile phones can be computed as follows:

$$\mathrm{FD} = n = 1 + b_2 e^{(-a_2 t)} t = \frac{ln\left(2-\sqrt{3}\right)b_2}{a_2} - 2 = \frac{ln\left(2-\sqrt{3}\right)b_2 - lne^{2a_2}}{a_2} = \frac{ln\left(2-\sqrt{3}\right)b_2 \,/\, e^{2a_2}}{a_2}$$

$$\therefore \mathrm{FD} = 1 + b_2 \cdot \frac{e^{2a_2}}{\left(2-\sqrt{3}\right)b_2} = 1 + \left(2+\sqrt{3}\right)e^{2a_2} = 5.010 \quad \because a_2 = 0.036$$

Appendix A-3

Assimilation capacity z can be depicted as follows:

$$z = \frac{1}{1 + \frac{\Delta T_s \,/\, T_s}{\Delta T_i \,/\, T_i}} \cdot \frac{T_i}{T_s}$$

(See Watanabe et al. [25]).

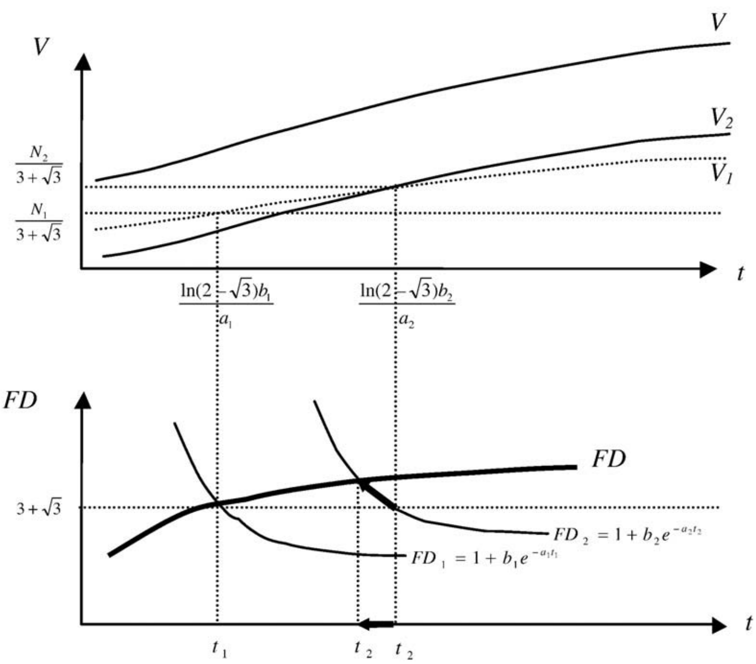


Fig. A3. Enhancement of the functionality development level as a consequence of the acceleration of its emergence.

Appendix A-4

FD in Eq. (18) can be obtained as follows:

$$\begin{aligned}\mathrm{FD} &= 1 + b(1 - a(T_i + zT_s)) \\ &= 1 + b - abT_i - abzT_s \\ &= 2 + (b-1)p + (b-1)q - abT_i - abzT_s \\ &= \left[1 + (b-1)p\left[1 - \frac{ab}{(b-1)p}T_i\right]\right] + \left[1 + (b-1)q\left[1 - \frac{ab}{(b-1)q}zT_s\right]\right] \\ &= [1 + b_1(1 - a_1T_i)] + [1 + b_2(1 - a_2zT_s)] \\ &\approx \left(1 + b_1e^{-a_1T_i}\right) + \left(1 + b_2e^{-a_2zT_s}\right)\end{aligned}$$

where $a_1 \equiv \left(\frac{ab}{(b-1)p}\right), a_2 \equiv \left(\frac{ab}{(b-1)q}\right), b_1 \equiv (b-1)p, b_2 \equiv (b-1)q$ and $p + q = 1$.

Appendix B. Predictive power of the model

From Eq. (2), functionality development can be depicted as follows:

$$\mathrm{FD} = \frac{N}{V(t)} = 1 + be^{-at} \approx 1 + b(1 - at) = \sum_{i=1}^{n}\,[1 + b_i(1 - a_it)] \approx \sum_{i=1}^{n}\left(1 + b_ie^{-a_it}\right)u\sum_{i=1}^{n} FD_i(t) \tag{A1}$$

where $a_i = \frac{ab}{b_i}\cdot P_i; b_i = [b - (n-1)]\cdot P_i; \sum_{i=1}^{n} P_i = 1;$ and $\mathrm{FD}_i(t) = 1 + b_ie^{-a_it}$.

This is equivalent to the successive FDs (FD_1, FD_2,..., FD_n) generated by the following multi-logistic growth model as

$$V = \sum_{i=1}^{n} V_i = \sum_{i=1}^{n} \frac{N_i}{1 + b_ie^{-a_it}} \tag{A2}$$

Given the logistic growth model, level and timing of inflection in diffusion trajectory can be identified by taking the first as well as the second derivative of the function as illustrated in Fig. A1.

As postulated by Mahajan et al. [18], diffusion trajectory shifts from increasing diffusion velocity to decreasing at the inflection point $t^{\#}$. Furthermore, increasing diffusion velocity shifts from "increasing faster" to "increasing slowly" at the earlier inflection point of the first derivative t_1, and decreasing diffusion velocity shifts from "decreasing slowly" to "decreasing faster" at the later inflection point of the first derivative t_2. In correspond to these inflection points, diffusion trajectory can be classified as (i) early adopters ($0 - t_1$), (ii) early majority ($t_1 - t^{\#}$), (iii) late majority ($t^{\#} - t_2$), and (iv) laggards ($t_2 - \infty$). Moreover, they identified that new functionality development emerged in the market at the transition from early adopters to early majority as gaining the use of the product and having a greater usage propensity. This transition timing corresponds to the diffusion changes from "increasing faster" to "increasing slowly" when it reaches to the level of $\frac{N}{3+\sqrt{3}}$ at time $\frac{ln(2-\sqrt{3})b}{a}$ as illustrated in Fig. A1. This suggests that the level of functionality development at its initial emergency corresponds to the level of $3 + \sqrt{3}$. Furthermore, it indicates that higher level of diffusion enables earlier timing of the emergence of functionality development with higher level as illustrated in Fig. A2.

Thus, higher level of diffusion accelerated by the innovation enables earlier timing of the emergence of functionality development with higher level as illustrated in Fig. A3. Eq. (8) depicts this trajectory.

Appendix C. Functionality development level of Japan's primitive mobile phones at their emergence

Primitive mobile phones emerged in Japan immediately after the start of high speed digital data link service (9600 bps) in April 1995. They disseminated substantially up until the emergence of the short message service (SMS) in June 1997. Their diffusion trajectory can be depicted by the following simple logistic growth function:

$$V(t) = \frac{N}{1 + be^{-at}}. \tag{2}$$

Therefore, their diffusion trajectory can be identified by means of a regression analysis over the period April 1995–June 1997 as summarized in Table A1[6].

From the estimated logistic growth function, functionality development of Japan's primitive mobile phones can be expressed as follows:

$$\mathrm{FD} = 1 + 3.105e^{-0.145t}$$

Utilizing the estimated logistic growth function, the timing of the emergence of the functionality development which corresponds to the timing of the shift from early adopters to early majority can be identified as December 1995 $\left(\frac{dV^2(t)}{dt^2} max.\right)$ as

[6] In this regression, the number of subscribers $V(t)$ over the period April 1995-December 1995 are estimated by the following correlation demonstrated by the regression analysis using actual data over the period January 1996-June 1997: $V(t)_{t=96/1-97/6} = \underset{(96.68)}{7.471} + \underset{(123.69)}{0.883t}$ adj. $R^2 = 0.999$.

Table A1
Estimates of logistic growth function in Japan's primitive mobile phones.

	N	a	b	adj. R^2
Parameter	28.669	0.145	3.105	0.992
t-value	24.73	18.36	17.56	

demonstrated in Fig. A4. The level of functionality development at this time can be computed as 3.838 as illustrated also in the same Figure.

Therefore, Japan's primitive mobile phones are estimated to emerge in December 1995 with the functionality development level 3.838.

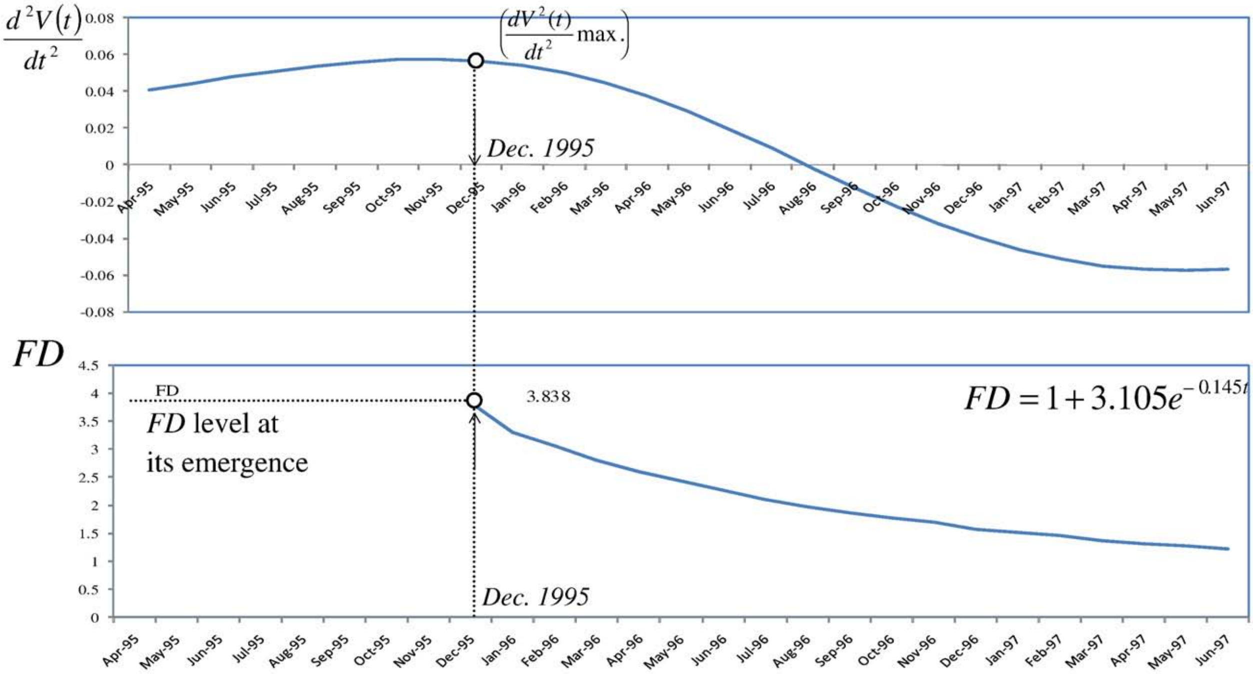


Fig. A4. Trends in secondary differentiation and FD in Japan's primitive mobile phones.

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