DEFINITION AND SUPPORT OF DIFFERENTIATION AND INTEGRATION IN MECHANICAL STRUCTURE USING S-CURVE THEORY AND WAVELET TRANSFORM

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Abstract

The differentiation and the integration of products are the essential procedures for product innovation. To understand the product innovation, the approaches using S-curve theory, which explain the evolution of a technological system, have been effective. However, the S-curve theory has the disadvantage that the validity of the analysis depends greatly on the number of data. In this paper, we propose a novel method for measuring and predicting the technological innovation and the product evolution based on the S-curve and wavelet transform to solve the problem. In order to confirm the effectiveness of the proposed method, we will conduct a case study using patents of air purifiers. Furthermore, we will define and support the differentiation and the integration of the mechanical structure using the proposed method. Our analysis shows that the differentiation and the integration of the mechanical structure occur as a life cycle extension after the main technologies enter the declining phase. Therefore, the incidental technologies should be introduced at the beginning of the declining phase of the main technologies.

Keywords: Innovation, Case study, Product Lifecycle Management (PLM), Decision making

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1 INTRODUCTION

Recently, to satisfy complex demands of consumers, multiple functions are continuously evaluated and implemented in various machines. The development and implementation of new functions have also advanced with the stronger relationship between the product evaluation and the technological improvements, which mainly depend on consumer judgments and market forces. Therefore, planning and realizing the proper correspondence between product functions and product development is significant to fulfil the various demands of consumers. How to find such correspondences? In devising a useful method to tackle this question, it is important for designers to manage properly (1) the differentiation caused mainly by the specialization of consumer demands, and (2) the unification caused mainly by the progress of integration and manufacturing technology.

Furthermore, the differentiation and the integration of products are the essential procedures for product innovation. The definition and support of these processes are relevant for the design of successful and innovative products with reasonable processes, such as those observed in the mobile phone and the DVD/hard disk recorder.

On the other hand, the importance of measurement, evaluation, and support of the innovation has increased due to market competition intensified by globalization. Especially, quantitative measurement and evaluation of the product innovation at the micro level, based on an understanding of the process of the innovation, have been necessary (NITSEP, 2007). In line of the above, the approaches using S-curve theory to explain the evolution of a technological system (Altshuller, 1984a) have been effective. For example, Chen Shiuan et al. (2010) indicated that innovative technologies lead to competitive advantage in the market and the extension of product life cycle; and Gizem et al. (2012a) estimated a trend of technology evolution of 3D television by using the S-curve theory to a number of patents.

S-curve theory is widely used in design and decision making as a versatile model of the technological evolution. However, as pointed out by Gizem et al. (2012b), the validity of the S-curve model largely depends on the number of data since the error occurs due to the deviation of data. In order to analyse the differentiation and the integration of the products, it is necessary to verify a few data such as patents of a single product and function. Therefore, there is a possibility that new knowledge can be obtained by tackling the above problem from a viewpoint, which is different from the conventional theory.

In this paper, we propose a novel method for analysing the technological innovation and the product evolution based on the S-curve and wavelet transform. Since the wavelet transform can obtain information of time as well as frequency, it is suitable for capturing the evolution process of the technologies in terms of time. Moreover, compared to the S-curve theory, our proposed method enables the precise analysis of temporal data since the step size of the data can be made finer by using the wavelet transformation. Thus, our proposed method is useful (1) to identify the interplaying factors included in the observation data by using wavelet transform and (2) to analyse the differentiation and the integration of products accurately. In particular, we analyse the time change in the maturity of the main and the incidental technologies in products by using compounded functions related to air purifiers as a target of the case study. Air purifiers are suitable for our case study because incidental functions such as humidification are sufficiently observed in products distributed in the market. We compare the transformed data and the S-curve model to analyse the life cycle of the technological system. Our analysis shows that the differentiation and the integration of products are phenomena, which occur after the main technologies enter the declining phase. Therefore, the incidental technologies, which are phenomena closely related to life cycle extension of products, should be introduced at the beginning of the declining phase of the main technologies.

In the rest of this paper, Section 2 overviews the S-curve of the technological system. Section 3 briefly overviews the wavelet transform. Section 4 describes the analysis model created by the S-curve theory and the wavelet transform. In Section 5, the proposed method is applied to "air purifier" to confirm its abilities and analyse the differentiation and the integration of products. Finally, section 6 concludes the paper summarizing our key results and future work.

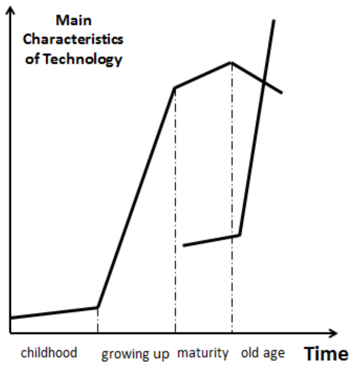

Figure 1. The life cycle of a technological system (Altshuller, 1984d)

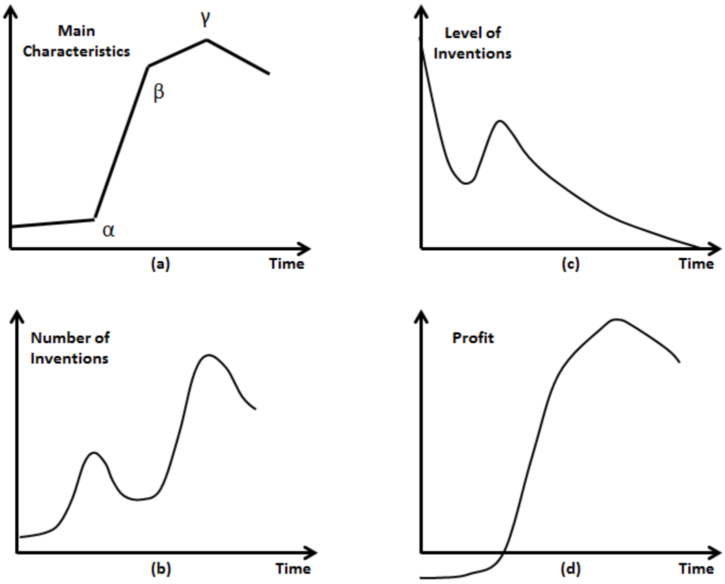

Figure 2. The factors of the technological system (Altshuller, 1984e)

2 S-CURVE OF TECHNOLOGICAL SYSTEM

The life cycle of a general technological system can be explained by the S-curve as shown in Figure 1. The vertical axis shows the main characteristics of the technology, and the horizontal axis shows the time. The life cycle of a technological system is divided into four stages, which are "childhood", "growing up", "maturity" and "old age" (Altshuller, 1984b).

Moreover, the transition of several factors belonging to the technological system is indicated as shown in Figure 2. The number of inventions is shown in Figure 2(b). This curve forms two peaks at the point α, which is the period of the transition to mass application, and the point γ, which is the period of the striving to prolong the life cycle of the system. The level of inventions is shown in Figure 2(c). The initial level, which represents the initial main inventions, is high and the level forms the peak at the period of the transition to mass production. The profit belonging to the technological system is shown in Figure 2(d). This curve implies that profit does not occur in the initial stage, but occurs in the mass production stage (Altshuller, 1984c).

The useful knowledge of the evolving technological evolution system can be obtained by comparing time series data belonging to the actual technology, for example the data from the number of patent applications and the profit brought by the products, with the S-curve model. Analysis of the evolving technological system using the S-curve theory is suitable for this research because it helps to obtain the diversified and systematic knowledge of the comprehensive life cycle of the multiple technologies. However, unlike the conventional system such as the extrapolation and other statistical methods, the S-curve method is not quantitative and cannot effectively assimilate numerical information. In order to tackle this weakness, we introduce the wavelet transform into the S-curve analysis.

3 WAVELET TRANSFORM

The wavelet transform is a functional expansion characterized by using a wave-like oscillation. The wavelet transform is different from function expansion using stationary wave like Fourier transform in that it can obtain both time and frequency information. The wavelet transform is suitable for analysing unsteady signals, such as sound since the resolution of time for high frequency components is high and the resolution of frequency is low for low frequency components (Masaaki, 1991).
In order to define the wavelet transform, we define mother wavelet $\psi(\mathrm{t})$, which is localized around the origin with width T. The wavelet function is obtained by scaling the mother wavelet by a parameter a and translating it by a parameter b.

$$\psi_{a,b}(t) = a^{-1/2}\psi((t-b)/a), \tag{1}$$

where $a^{-1/2}$ is a coefficient for normalizing the norm.
The wavelet transform of the function $f(x)$ is defined as

$$(W_{\psi}f)(b,a) = \int_{-\infty}^{\infty} 1/|a|^{-1/2}\,\overline{\psi((t-b)/a)}f(t)dt. \tag{2}$$

The value of $(W_{\psi}f)(b,a)$ increases when the function $f(x)$ is sufficiently similar to the wavelet $\psi(\mathrm{t})$. Conversely, the value of $(W_{\psi}f)(b,a)$ decreases when the function $f(x)$ is sufficiently similar to the wavelet $\psi(\mathrm{t})$.
A representation of the function $f(x)$ can be obtained by performing this calculation for every a and b and plotting the value of the wavelet transform $(W_{\psi}f)$ on the signal plane, whose vertical axis is $1/a$ and horizontal axis is b.
The operation of restoring the original signal $f(x)$ from the transformed data is called inverse wavelet transform, which is given as

$$f(x) = 1/C_{\psi} \int\int_{\mathbb{R}^2}(W_{\psi}f)(b,a)\ (1/|a|^{-1/2})\ \psi((t-b)/a)\ dadb/a^2. \tag{3}$$

In order to be able to define the right side of this expression, the following admissible constant must be satisfied (Susumu, 1995).

$$C_{\psi} = \int_{-\infty}^{\infty}(|\hat{\psi}(\omega)|^2/|\omega|)\,d\omega < \infty. \tag{4}$$

Thus, the wavelet transform can visualize the hidden characteristics of a signal on a two-dimensional signal plane. The waveform represented in the S-curve of the technological system is still a signal acquired at every fixed time and the signal will fluctuate unsteadily and irregularly under complicated factors. Wavelet transform is suitable for quantitative processing of such signals and it is possible to conduct systematic discussions on transformed data using S-curve theory. However, we further create a model of innovation from the extension of the S-curve theory and apply wavelet transform based on the model in order to analyse effectively and exclude subjectivity of analysts.

4 PROPOSED ANALYSIS MODEL

In this paper, we analysed the number of patents considered as the number of inventions, which is advocated in the evolution theory of the technology system. The curve model of the number of inventions was expanded, as multiple innovations exist in one technological system. In the expanded model, each innovation shows the transition of the number of inventions as mountain-like figures. The transition of the number of inventions of the entire technological system is formed by superimposing each innovation (Figure 3).
The group of inventions to which one innovation belongs follows the growth process, which starts from the dawning and finishes at technological or economic limitations. Therefore, a logistic function, which is known as a model of population growth, was used as a mathematical model of the transition of the number of inventions. The logistic function is given as

$$\mathrm{N(t)} = l/(1+me^{-nt}), \tag{5}$$

where l, m and n are constants and t is a variable of time.

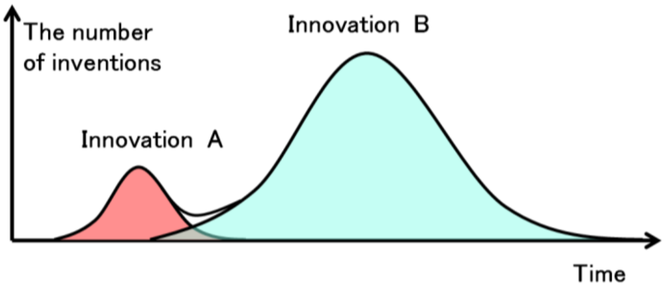

Figure 3. The superimposition of innovations

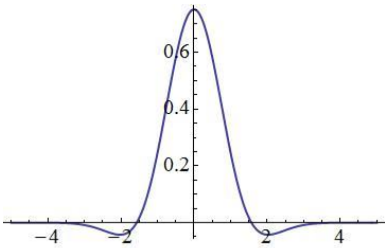

Figure 4. Gabor Wavelet

The curve drawn by the number of inventions is not the cumulative value but the rate of increase according to the model of Altshuller (Figure 2(a)). Therefore, the expression of the growth rate of the logistic function obtained by differentiating equation (5) for the mathematical model should be used.

$$\mathrm{N}'(\mathrm{t}) = lmn\, e^{-nt}/(1 + me^{-nt})^2. \tag{6}$$

By using this function as a wavelet and performing wavelet transform on the transition of the number of patent applications, the fitness of innovations with different length of time and different timing of occurrence is quantitatively visualized. However, since this expression does not satisfy the admissible constant of the wavelet, the Gabor wavelet, which has similar shape to the logistic function, is used for analysis (Figure 4). The function of Gabor wavelet is defined as follows:

$$\psi(\mathrm{t}) = \left(1/\sqrt[4]{\pi}\right)e^{(ix)}e^{(-x^2/2)}. \tag{7}$$

5 THE EXAMPLE ON AIR PURIFIER TECHNOLOGY

The proposed method is applied to "air purifier" to confirm its abilities. Since air purifiers are industrial products that succeeded not only by the main application of cleaning the air but also by incorporating incidental functions such as humidification and sterilization into multifunctional products, they are suitable for the case study of the differentiation and the integration of products.

By using our proposed method to the main technology of air purifiers belonging to the functions of cleaning air, and the incidental technology of air purifiers belonging to the functions typified by humidification, we aim at defining the phenomenon of product differentiation and integration and the timing of its occurrence.

5.1 Extraction of patents

A patent group relating to air purifiers applied in Japan was used as a subject for performing wavelet transform based on the model of a number of inventions. The patent retrieval system provided by the National Centre for Industrial Property Information and Training and the Institute of Intellectual Property were used for acquiring patent information. Here, IPC, FI, and F term were used for extracting patents of air purifiers. IPC is a patent classification determined by international treaties. FI is a Japanese unique classification method characterized by subdividing IPC. F term is a Japanese unique classification method, which classifies patents from a viewpoint different from the hierarchical structure of IPC.

Since the air purifiers are characterized by performing ventilation and by separating dispersed particles from the air, the technologies concerning ventilation and separation of particles were extracted as the

Table 1. Searching method

Technology	Period	Classification	Searching equation
Ventilation	1970-2010	IPC and FI	F24F7/00@A + F24F7/00@B
Particles separation	1970-2010	F term	3L055-AA07
Humidification	1970-2010	F term	4D054-AA11

Table 2. Meaning of the searching codes

Codes	Contents
F24F7/00@A	Something which ventilate while cleaning air
F24F7/00@B	Air purifiers including ion generators
3L055-AA07	Humidification-Equipment with a humidifier-Air purifiers
4D054-AA11	Electrostatic separation-Use-Air purifiers

main functions of the products. The technologies concerning humidification were also extracted as an integrated mechanical structure into air purifiers.

Though these technologies are covered by IPC, search by IPC cannot satisfy the intention of this case study for air purifiers because other technologies, which are not related to air purifiers, are also extracted. Therefore, it is necessary to extract technologies relating to air purifiers with utmost accuracy, by using FI and F terms, which are more detailed and more specific than IPC.

Table 1 shows the searching method for extracting these technologies. Table 2 explains the meaning of the searching codes (Japan Patent Office, 2016a, 2016b).

5.2 Verification of proposed method

In order to verify the features of the proposed method, the transition of the number of patent applications of the technologies belonging to the air purifier and the scalogram of these technologies are illustrated in Figures 5-9. In particular, Figure 5 shows the annual number of patent applications of the technology belonging to the air purifiers. Figure 6 shows the quarterly number of patent applications of technology belonging to the air purifiers. Figures 7, 8, and 9 show the annual and quarterly scalograms of three technologies belonging to the air purifiers.

Since Gabor wavelet is a wavelet with a width of 4 (Figure 4), a wavelet representing the innovation of 4 years is used if the scale is 1, and that of 20 years is used if the scale is 5 in the annual scalograms.

Short-term trends and long-term trends are distinguished by scales, and the integrated observation of these different trends by using the scalogram is the feature of this method.

In addition, Figure 7, 8 and 9 show that similar results can be obtained by using our method even if the time interval of data acquisition is reduced. This fact confirms that our method is able to cope not only with limited data, but also with fine-grained data; which is otherwise difficult to handle at first glance in the S-curve model as shown in Figure 6. Thus, the proposed method offers a complementary perspective to the conventional S-curve theory.

5.3 Differentiation and Integration of mechanical structure

In order to analyse the occurrence of the differentiation and the integration in the air purifier, which is defined as the phenomenon wherein the incidental technologies such as humidification technology are integrated into the main technologies (ventilation and separation of particles), Figures 7-9 show the transformed scalograms between 1970 and 2010.

Observing the ventilation technology as shown in Figure 7, a dense area appears at the large-scale area between 1980 and 1990. Although the trend falls approximately around 1990, the strong innovation occurs to take a peak in the first half of the 2000s. Observing the particle separation technology as shown in Figure 8, a strong innovation, which consist of two short-term mountains, first occurs between 1980 and 1990. After another short-term innovation in the first half of the 2000s, the density of areas at large scale gradually becomes thinner. The fact that two mountains of innovations occur in the 1980s and 2000s is common to these two technologies.

We discuss this result using the product history of the air purifiers. According to Panasonic Ecology System Co., Ltd. (2016), the period between 1981 and 1990 is the "embryonic period" of air purifiers, when small household products appeared in Japan. The period from 1997 onwards is the period of "maturity period" of air purifiers when product applications have been expanded.

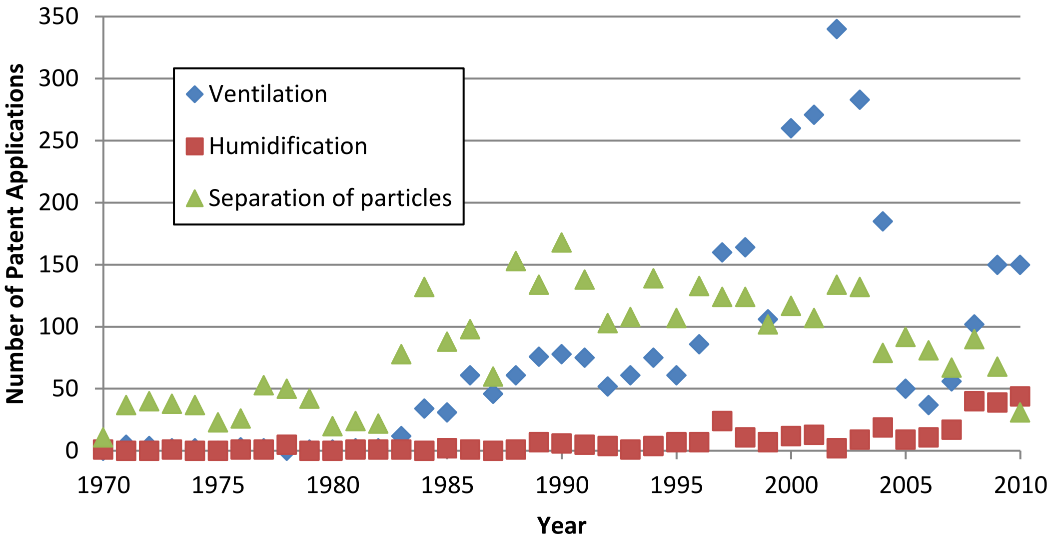

Figure 5. Annual patent applications of air purifier technologies

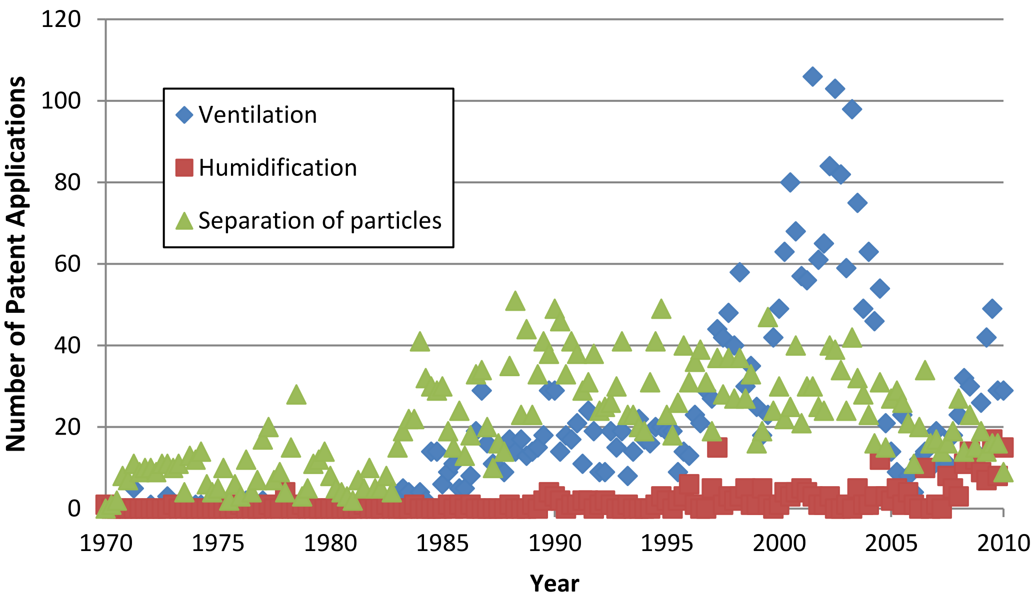

Figure 6. Quarterly patent applications of air purifier technologies

According to Chunichisya Co., Ltd. (1996), it is said that "Air purifiers as a single product are often regarded as ceiling" at 1996, and the shipment value peaked in 2002 and turned to a downward trend (Chunichisya, 2007, 2011).

By combining the results of the wavelet transform with the product history described by Panasonic Corp., it becomes clear that innovation appears at the mass production period and the peak period. This result is consistent with the theory of the number-of-applications model introduced in Section 2, and therefore confirms that this method quantitatively expands the model of Altshuller. Therefore, air purifiers reach the "growing up" period in the 1980s and reach the "old age" period in the 2000s.

Regarding humidification technology, which is a technology attached to air purifiers, we show that strong innovation occurs only in the 2000s. This result implies that the innovation of humidification technology occurs after the "old age" period, while it does not occur in the "growing up" period. Thus, in the air purifier, the innovation of the ventilation technology and the particle separation technology decline at the "old age" period, and conversely, that of the humidification technology became flourishing. Such change of the innovation from the core technology to the incidental technology is the differentiation and integration of mechanical structure in the air purifier.

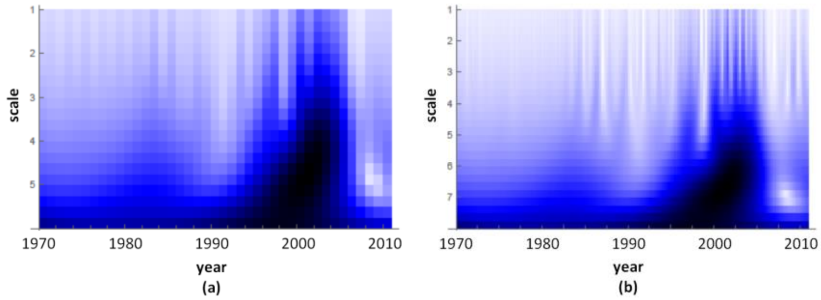

Figure 7. (a) Annual scalogram, (b) Quarterly scalogram of ventilation technology

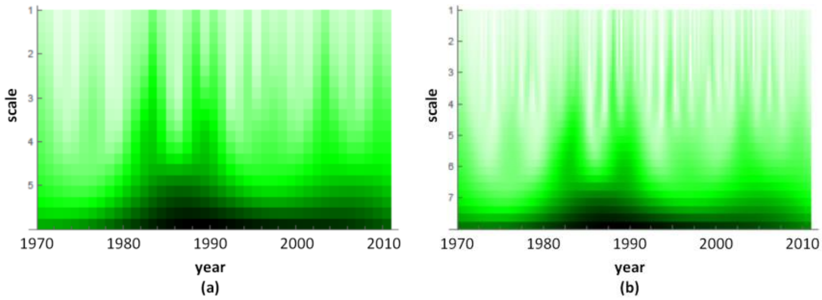

Figure 8. (a) Annual scalogram, (b) Quarterly scalogram of particles separation technology

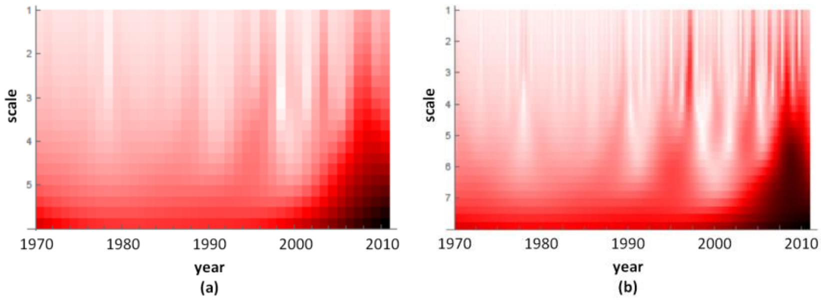

Figure 9. (a) Annual scalogram, (b) Quarterly scalogram of humidification technology

Thus, the differentiation and the integration of the mechanical structure is a phenomenon as an extension of the life cycle of the technology, and therefore this phenomenon can be predicted reasonably by estimating the time when the "old age" phase of the main technologies of the products begin. Further studies to generalize our method and insights to a larger set of mechanical systems are in our agenda.

5.4 Discussion

In this section, in order to discuss the challenges when predicting the differentiation and the integration of the air purifier system during the transition of "growing up" or "maturity" period, Figures 10, 11 and 12 show the scalograms of the technologies of the air purifiers from 1970 to 1990 and from 1970 to 2000, respectively.

As we can observe, Figure 10a and 11a indicate that innovation occurs in the 1980s (dark area) and that trend continues in the immediate vicinity of 1990 (continued dark area). As mentioned in Section 5.3, this innovation is observed at the mass production period. However, no pattern of "old age" period occurs in these scalograms. Also, Figure 10b and 11b indicate that innovation remarkably occurs in the ventilation technology near 2000 (dark area increases significantly towards 2000), whereas such innovation does not occur in the particle separation technology. Thus, since the innovation clearly occurs in the ventilation technology near 2000, which is different from that in the mass production, it is possible to conjecture that this is an innovation in the decline period.

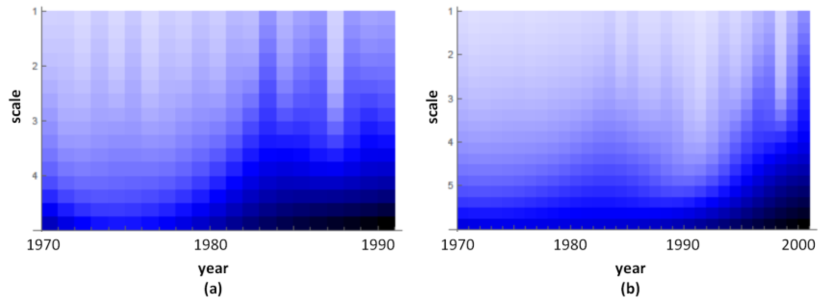

Figure 10. Scalograms of ventilation technology (1970-1990(a), 1970-2000(b))

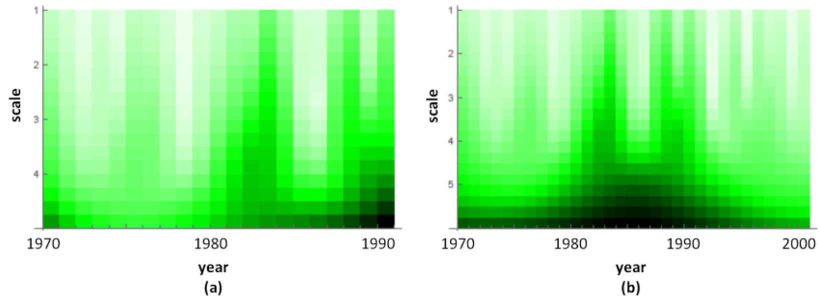

Figure 11. Scalograms of particles separation technology (1970-1990(a), 1970-2000(b))

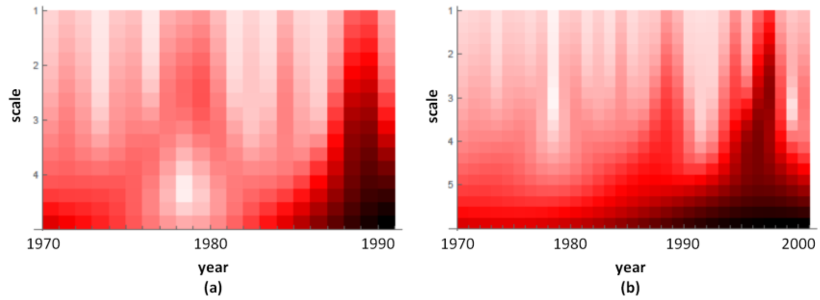

Figure 12. Scalograms of humidification technology (1970-1990(a), 1970-2000(b))

On the other hand, Figure 12 indicates that the innovation occurs in the humidification technology in the vicinity of 1995, but the beginning of innovation that occurs after 2005 as shown in Figure 9 cannot be observed. We consider that it is difficult to predict the trend of innovation from these scalograms because there are very few patent applications in humidification technology before 1996 (Figure 5).

Thus, the prediction of the "old age" period using the proposed method is possible by grasping the beginning of innovation occurring in the "old age" period. However, the prediction of the "old age" period in the "growing up" period and the estimation of the precise time of the "old age" period will be both difficult. Regarding the prediction of the peak time, that is, the prediction of sudden change of trend, the proposed method will have a certain limitation. In actual decision making, the prediction of the "old age" period should be made by using these scalograms in combination with the indicators of the market environment such as the number of shipments and the penetration rate. However, in Japanese public statistics, information on the number of shipments of air purifiers does not exist before 2003 (METI, 2005) and information on the penetration rate of air purifiers does not exist before 2006 (CAO, 2017).

As confirmed in Section 5.3, the differentiation and the integration of the mechanical structure occur in the "old age" period of the main technologies of the product. Therefore, by predicting the occurrence of the "old age" period, it may be possible to estimate the timing of the multi-functionalization and the single-functionalization of the products. We believe that by using different types of market information mentioned above, will enable the estimation to support the decision making of the corporate activities such as research, development and marketing.

6 CONCLUSION

We have proposed a method to support the analysis of differentiation and integration of an evolving technological system. The unique points of our work are: (1) to propose a novel method to understand the evolution of a technological system by using wavelet transform and S-curve theory, which is expected to be more precise compared to the conventional evolutional theory; and (2) to analyse the differentiation and the integration of the air purifier technology comprehensibly over the period of 1970-2010 by using information from the Japanese patent office. Our analysis has shown that differentiation and integration in the air purifier is a phenomenon occurring at the declining phase of the main technologies (ventilation and separation of particles). Therefore, estimating the time when the declining phase begins is necessary for decision making of single-functionalization (differentiation) and multi-functionalization (integration). In addition, the evolution theory of the technological system is quantitatively expanded by the wavelet transform of the number of applications of patents. In order to predict the declining period accurately, it becomes essential to not only analyse several technologies belonging to the product, but also to use parameters of the market environment such as the number of shipments and the penetration rate to understand the evolution of a technological system. Further studies to generalize our method and insights to a larger set of mechanical systems are in our agenda. We believe that analysing further technological systems and verifying various parameters such as market data will provide an accurate prediction and support system to aid decision making of the differentiation and the integration of the mechanical structures.

REFERENCES

Altshuller, G. (1984a), *Creativity As An Exact Science*, Gordon and Breach Publishers, Newark, p. 205.

Altshuller, G. (1984b), *Creativity As An Exact Science*, Gordon and Breach Publishers, Newark, p. 206.

Altshuller, G. (1984c), *Creativity As An Exact Science*, Gordon and Breach Publishers, Newark, pp. 209-210.

Altshuller, G. (1984d), *Creativity As An Exact Science*, Gordon and Breach Publishers, Newark, p. 207.

Altshuller, G. (1984e), *Creativity As An Exact Science*, Gordon and Breach Publishers, Newark, p. 207.

Chen Shiuan, L., Hiroshi, H. (2010), "Analysis of a Technology System Evolution by Focusing on a Technology Maturity," *Design and Systems Division Conference*, Tokyo, Oct. 27-29, 2010, The Japan Society of Mechanical Engineers, 2302.

Chunichisya Co., Ltd. (1996), *Denshi-kiki nenkan 1996*, Chunichisya Co., Ltd., Tokyo, p. 299.

Chunichisya Co., Ltd. (2007), *Denshi-kiki nenkan 2007*, Chunichisya Co., Ltd., Tokyo, p. 471.

Chunichisya Co., Ltd. (2011), *Denshi-kiki nenkan 2011*, Chunichisya Co., Ltd., Tokyo, p. 455.

Gizem, I., Tufan, K (2012a), "The Use of S Curves in Technology Forecasting and its Application On 3D TV Technology", *International Scholarly and Scientific Research & Innovation* , Vol. 6, No. 11, Available at: waset.org/Publication/13173 (Jun. 7, 2016).

Gizem, I., Tufan, K (2012b), "The Use of S Curves in Technology Forecasting and its Application On 3D TV Technology", *International Scholarly and Scientific Research & Innovation* , Vol. 6, No. 11, Available at: waset.org/Publication/13173 (Jun. 7, 2016).

Japan Patent Office, (2016a), *FI kaisei jouhou*, [online] Available at: (http://www.jpo.go.jp/shiryou/s_sonota/f_i_kaisei.htm) (Dec. 2, 2016).

Japan Patent Office, (2016b), *F term theme code ichiran jouhou*, [online] Available at: (http://www.jpo.go.jp/shiryou/s_sonota/themecode.htm) (Dec. 2, 2016).

Masaaki, S. (1991), "Mathematical foundation of wavelets I. Non-orthogonal wavelets", *The Journal of the Acoustical Society of Japan*, Vol. 47, No. 6, pp. 405-415.

Ministry of Economy, Trade and Industry (2005), *Yearbook of Machinery Statistics*, Research Institute of Economy, Trade and Industry, Tokyo, p. 213.

National Institute of Science and Technology Policy (2007), *Preliminary Study on the Measurement of Innovation*, Ministry of Education, Culture, Sports, Science and Technology, Tokyo.

Panasonic Ecology System Co., Ltd. (2016), *Rekishi hakubutsukan Kukiseijo-ki*, [online], Panasonic Ecology System Co., Ltd.. Available at: (http://panasonic.co.jp/es/peses/showroom/museum/03.html) (Dec. 7, 2016).

Susumu, S. (1995), *Wavelet Beginner's Guide*, Tokyo Denki University Press, Tokyo.