Research on the Logic of Product Evolution Using Agent-based Model

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Abstract--**This research makes use of an agent-based model that simulates the product evolution affected by the producer's routine, consumer's preference, and complementarity of the product's features. We identify that the velocity of product evolution increases when the heterogeneity of producers or consumers and the complementarity between features increase. We draw some implications based on the results. In respect to policy, we see the need to create a favorable environment for heterogeneous producers to participate in the market to enhance competition. In respect to product development strategy, we see the need to focus on highly complementary technologies.**

I. INTRODUCTION

With dramatic ongoing changes in technology and the associated human needs, new products continually appear and disappear from the marketplace. Under these circumstances, products are continuously evolving in a process similar to that of the evolution of an organism. If we can understand the logic and critical factors underlying this product evolution, we can identify the general principles that are embodied in this evolution. Furthermore, we can predict the direction of the evolution of the product.

Since the product is the medium that connects the producer with the consumer, we focus on three aspects of producer, consumer, and product to identify the product evolution principles. From the view of the producer, many studies show that producers' routines affect product innovation or evolution [1, 2, 3]. From the view of the consumer, some studies are concerned with consumer demand and technology innovation [4, 5, 6]. These show how the consumers' preferences, such as heterogeneity of demand, affect product innovation. From the view of the product, the technology and service evolution that is inherent in the product also relates to the product evolution [7].

In this study, we suggest a logic underlying product evolution and new implications from the perspective of product evolution by examining the interactions among the producer's routine, the consumer's preference, and the product characteristics using an agent-based model (ABM). Specifically, we are concerned with how fast products evolve and which conditions drive the velocity of the product evolution.

This paper is organized as follows: Section 2 reviews the related literature; Section 3 proposes our hypotheses; Section 4 describes our methodology and the model; Section 5 interprets the results; and, our final section presents some concluding remarks.

II. LITERATURE REVIEW

When several systems coevolve, they have a causal influence on each other's evolution [8]. Products often coevolve and interact with human activities, satisfying the evolutionary conditions of Universal Darwinism of variation, selection, and replication [9, 10].

Evolution studies on the producer's routine are mainly based on Nelson and Winter's evolution model [1]. This research shows that agents with bounded rationality act, learn, and explore through their experience with an uncertain and changing environment using the trial and error method. Such agents act according to routine and market competition and their knowledge generates certain approaches and systematic methods. A producer's routine is inheritable similar to the gene of an organism and is determined by an accumulation of the producer's past experiences. It can also be considered a unique characteristic of the producer that can neither be imitated nor transferred. Hence, a routine accrues from what the producer has experienced in the market and a producer strategy is then developed based on this routine. Thus, it is likely that the variety of producer routines that exist are not independent but rather are coevolving through market interactions.

One consumer pattern is preference for one product over another. However, preferences do change as in the following three ways [11]. First, shifts in the sociopolitical environment including regulation, new legislation, political turmoil, or other exogenous shocks, can change user preferences. Second, when a product is part of a broader modular system, interdependencies and shifting bottlenecks can create new functionality and/or performance requirements. Third, the evolution of customers over time, including their increased size and complexity or expanded applications of the technology after prolonged experience, can fundamentally change needs. Those preference discontinuities can create product evolution. Researchers, including Christensen and Adner, show how heterogeneous consumer preference interacts with the technology evolution of the product [4, 5, 6]. Rogers' diffusion model shows that innovation adoption has an effect on the selection of the products [12, 13, 14, 15]. Such studies may be concerned with the co-evolution of consumers and products.

Saviotti and Metcalfe [16] propose to describe technologies in terms of both technical and functional attributes in the same way as in genotype-phenotype maps. We can understand this first concept as product evolution. The second concept that we examine is the NK model developed by Kauffman and Weinberger [17]. The NK model could show evolution by a simple model and simulation methodology. Ahrweiler et al. suggest an agent-based simulation model representing a theory of the dynamic processes involved in the innovation of modern knowledge-based industries [18]. They identify products as being composed of kenes defined as knowledge units. Ma and Nakamori [3] demonstrate a multi-agent model built to simulate the process of technological innovation, based on the widely accepted theory that technological innovation is an evolutionary process. They add environmental selection into the simulation and explore technological innovation as the result of the interaction between construction and environment selection.

In summary, using the concept of Universal Darwinism, we could define the system as evolving if the system satisfies the conditions of variation, selection, and replication. Products are created with variation through the producer's innovation, and are sold according to consumers' preferences in the market. Prior characteristics of best-selling products are transferred to newly developed products. The products evolve because they can satisfy the evolutionary conditions of Universal Darwinism including variation, selection, and replication. However, products cannot evolve alone; they evolve from the interactions between producer and consumer.

Stylized facts about product evolution

These stylized facts represent theoretical and empirical research results, scientific methodology that compares hypotheses and verifies our simulation model.

With respect to the producer's routine, when a producer innovates, products can evolve. In evolutionary economics, the more research and development (R&D) resources there are, the higher the probability for successful innovation and the velocity of the product evolution increases [1]. On the other hand, imitation could have a direct effect on the velocity of developing technologies for products. This is because imitation is the replication of the evolved technology and not the evolution of that technology. In addition, radical innovation means creating new product types, which do not exist in the current market, and means creating different processes from incremental innovation [19]. From those facts, we could draw the following stylized facts.

Stylized fact 1-1. When the ratio of a producer's radical innovation routine increases, the velocity of introducing new product characteristics increases.

Stylized fact 1-2. When the ratio of a producer's incremental innovation routine increases, the velocity of developing current product characteristics increases.

Stylized fact 1-3. When the ratio of a producer's imitation routine increases, the velocity of innovation does not change.

From the view of the consumer, consumers also have an important effect on product evolution. Particularly, consumer preference for new product features is an important factor for product diffusion [20, 21, 22]. By discovering exact consumer preferences, product evolution will quicken. The greater a consumer's preference for a new feature, the faster the product diffusion and product evolution.

Stylized fact 2. When the preference of a consumer for new product characteristics increases, the velocity of product evolution increases.

When a new characteristic of a product is developed or added through R&D, the product may have evolved. Therefore, if the probability of success for the invention is high, product evolution velocity increases [1].

Stylized fact 3. When producers easily invent new product characteristics, the velocity of product evolution increases.

III. HYPOTHESES

We present the stylized facts around the producer and consumer routines and product evolution velocity based on generalized research and observed results. We try to posit our hypotheses from the view of product evolution based on the stylized facts. This study searches the logic of product evolution, and explores the interactions among products, producer routines, and consumer routines from the view of an evolution eco-system.

In the research of Nelson and Winter [1], producers have static routines and dynamic routines. The static routine means that such producer maintains his/her routine when the environment changes, while the other producers that have dynamic routines change their routines. In general, a dominant producer cannot try to change his/her innovation routine. For example, producers in the electrical and electronic market are less sensitive to radical innovation than to incremental innovation [23]. In the drug market, dominant producers try to innovate radically [24]. Stylized facts 1-1, 1-2, and 1-3 also show that when producers change their innovation routines, they affect the product evolution in the static condition.

However, producers could change their routines based on competition so that these changes create heterogeneity among producers. The heterogeneity of producer routines creates various innovations [1, 25, 26]. Therefore, we draw a hypothesis as follows:

Hypothesis 1. When the heterogeneity of producers increases, the velocity of product evolution increases.

According to stylized fact 2, the velocity of product evolution increases when consumer preference for new product characteristics increases. Furthermore, the heterogeneity of consumers has an important effect on the variety of products [5, 27] and product diffusion [28]. Therefore, we draw a hypothesis as follows:

Hypothesis 2. When the heterogeneity of consumers increases, the velocity of product evolution increases.

New products are made are more complex and producers apply various technologies to these products. Applying new technologies creates new interactions with current technologies [27, 29, 30] and causes complementarities among technologies. Such complementarities make new feature introduction easy and product novelty higher [31]. Therefore, producers invent new product characteristics easily because of complementarities while product evolution velocity increases as stated in stylized fact 3. This means complementarity among product features make current features better, the level of novelty higher, and can increase the product evolution velocity. Therefore, we draw a hypothesis as follows:

Hypothesis 3. When the complementarity between product characteristics increases, the velocity of product evolution increases.

IV. METHODOLOGY

We set producers as agents $P = \{P_1, \dots, P_s\}$, and consumers as agents $C = \{C_1, \dots, C_R\}$. Every period, producers make products with their own product features. Each product has N design parameters $G = \{g_1, \dots, g_N\}$ that represents function $F = \{f_1, \dots, f_U\}$. Each function has K unit connections among design parameters and consumer weight $W = \{w_1, \dots, w_U\}$. Consumers consider functions and weight and then make a decision to buy products by the maximization utility.

We set the producer as having three routines: radical innovation, incremental innovation, and imitation. Consumers have a search pattern and preference pattern for products.

Each producer has an innovation strategy (routine) in the product development step, and these differ from each other. The producer decides the quantity from the selling information in the market. The consumer has strategies for searching for and purchasing products. The search strategy captures the range of product information. The purchasing strategy captures product preference and innovation adoption in the consumer routine.

The simulation steps are as follows: First, producers analyze the features of the best-selling product in the market and develop innovations based on their own innovation routines. The innovations change the design parameters of products and the performance of the function parameters. When producers sell the products in the market, consumers search and buy these products. Consumers make a decision to purchase according to their preference structure and innovation adoption. Consumers buy products according to utility maximization. Each producer knows all product sale quantities in the market. When a producer sells out, the next period producer increases output quantity; otherwise, the producer decreases output. After a producer analyzes the best-selling product in the market, the same steps are repeated.

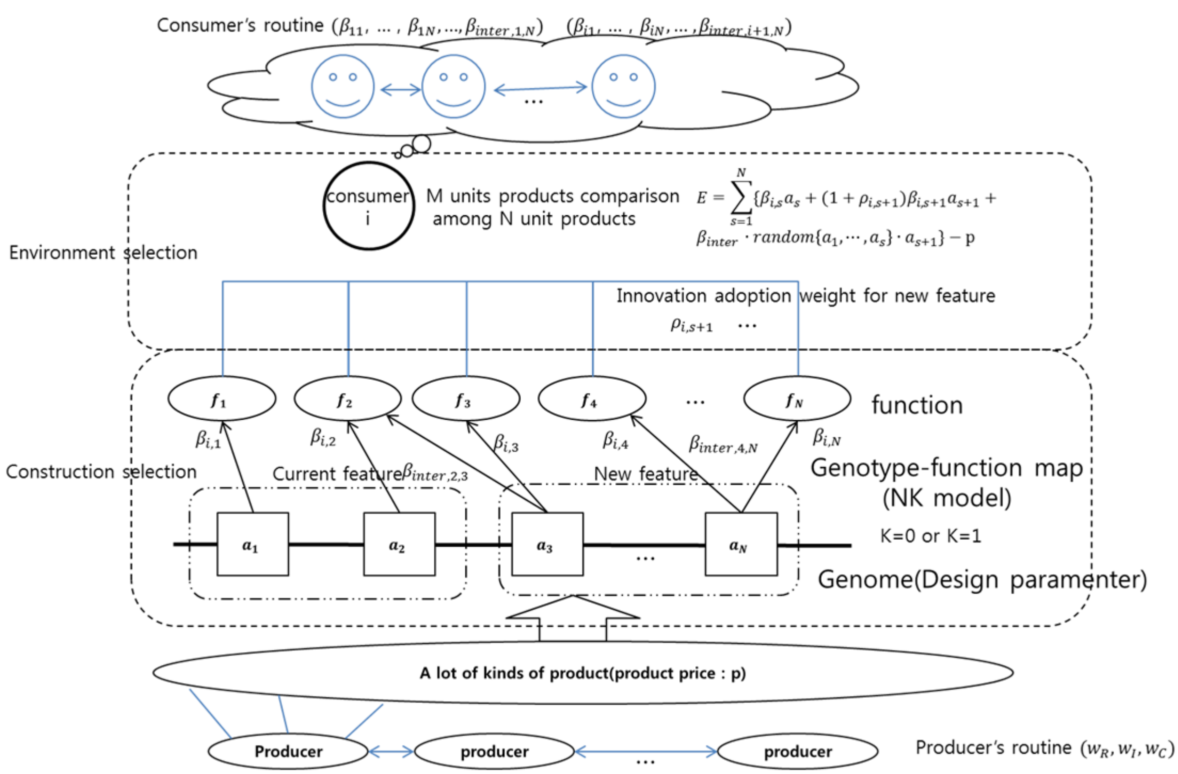

Fig. 1. Model's concept

Producer i has a separate routine for investing R&D, with I_i for the radical, incremental, and imitation routine. All Routines of the producer have a radical innovation weight w_R, incremental innovation weight w_I, and imitation weight w_C. Their sum is $1 (w_R + w_I + w_C = 1)$.

Each consumer i has a preference set $\{\beta_{i,1}, \dots, \beta_{i,S}\}$ for product features {1, …, S}. When a new product feature is available, the consumer has a new preference ($\beta_{i,S+1}$). When a new feature is added, one of the current features has a relationship with the new feature and it has an additional preference($\beta_{inter,S}$). When a radical innovation succeeds and a new feature is added, the consumer adopts the innovation of the new feature and the preference weight for the new feature(β_{wow}).

The product is composed of features and represents as $Prod_i = \{a_1, a_2, \dots, a_j, \dots, a_n\}$. a_j is the quality of each feature of the product. The quality of the feature increases by one unit when the innovation of each feature is successful. Initially, the number of all features is N and the initial products have a minimum of two features and one quality for each initial feature. When radical innovation succeeds, the level of quality of the feature is one. When incremental innovation happens, the level of quality adds one. Incremental innovation means that the best quality of a product feature in the market adds one level of quality in the simulation. Imitation means that the low level quality of a product feature catches up to the best quality feature in the market. In the innovation process, we set the number of product features that are possible to copy($count_I$), the number of product features possible to innovate incrementally($count_I$), and the number of product features possible to innovate radically($count_R$). The producer invests R&D resources based on these results.

All producers use the best practice to decide their innovation methods. In this study, the best practice is defined as the best-selling product in the market; this product represents the best practice and producers make a decision by using this product. Each product has the price(P). Each product feature has a relationship with each other feature as in the NK model, and the relationships create the performance of the product functions. We set $K \leq 1$, as a kind of generalized NK model.

There is a different success probability for each type of research: radical, incremental, and imitative innovation. We set the coefficient of the radical innovation success probability(P_R), the coefficient of the incremental innovation success probability(P_I), and the coefficient of the imitation success probability(P_C). Radical innovation success probability is $P_{R_f} = P_R w_R I_i$. The radical innovation and imitation success probabilities are $P_{I_f} = P_I w_I I_i / count_I$ and $P_{C_f} = P_C w_C I_i / count_C$, respectively.

Consumer C_j (j=1, …, $N_{total\ consumer}$) makes a decision by a hedonic utility function. Every consumer has hedonic coefficients for all product features $\beta_{Cj} = \{\beta_{1Cj}, \cdots, \beta_{UCj}\}$. When a new feature is added to a product, the consumer utility is $U_{consumer_i,\, total}$ when $random\{a_1, \cdots, a_s\}$ means that one quality of the feature is randomly selected among all features.

$$U_{add} = (1 + \beta_{wow})\beta_{i,s+1} a_{s+1} + \beta_{inter} \cdot random\{a_1, \cdots, a_s\} \cdot a_{s+1}$$

$$U_{consumer_i,\, total} = \sum_{s=1}^{s} \beta_{i,s} a_s + (1 + \beta_{wow})\beta_{i,s+1} a_{s+1} + \beta_{inter} \cdot random\{a_1, \cdots, a_s\} \cdot a_{s+1}\} - p$$

The baseline model and initial conditions are described in Appendix 1. In addition, we compare the results from our model with the results of Ma and Nakamori [3] in a similar situation to check the validity of our model, as shown in Appendix 2.

TABLE 1. THE SUMMARY OF AGENT RULES

Agent	Description of Rule
Producer	**When there are products from 1 to p, the best product is the highest selling product in the market and the product is the object of imitation.** $\mathbf{Best\ Product = \max\{Sale_1, \dots, Sale_p\}}$ **First producer finds the best product in t-1 period in the market and creates a strategy on the output, R&D investment.** **Producers innovate by their radical, incremental, and imitative routines.** **When producer i supplies output $P_{q_i} \leq$ Demand quantity $Sale_i$, next period producer increases output by using the increment coefficient $c_{q_{inc}}$.** $\mathbf{P_{q_i,t+1} = (1 + N_{total\ consumer}/P_{q_i,t} \times c_{q_{inc}}) \cdot P_{q_i,t}}$ **When producer i supplies output $P_{q_i} >$ Demand quantity $Sale_i$, next period producer decreases output by using the decrement coefficient $c_{q_{dec}}$.** $\mathbf{P_{q_i,t+1} = P_{q_i,t} - c_{q_{dec}} \cdot (P_{q_i,t} - Sale_i)}$
Consumer	**When there are m products in the market, consumers compare p products among n products and their utilities.** **When consumers compare products from 1 to p, they select the product that satisfies maximum utility, $\max\{U_1, \dots, U_p\}$.** **When a producer adds a new product feature, a_{s+1}, the product has the additional preference $((1 + \beta_{wow})\ \beta_{s+1})$.**

V. SIMULATION RESULTS

Table 2 presents the values of product evolution velocity, the mean of the maximum values of each feature, and the number of revealed features, the mean of the number of revealed features($a \geq 1$) in the final period(T=50). To test hypothesis 1, we compare our baseline model with a model of homogenous producers with the same innovation routine (w_R, w_I, w_C=0.33, 0.33, 0.34).

The velocity values of feature one and two in the baseline model are significantly larger than in the homogenous routine model, which indicates that the velocity of product evolution increases when the heterogeneity of producers increases. Additionally, when producers have different innovation routines in the market, the products tend to have more functions originating from more features.

Table 3 shows the results from testing hypothesis 3. Here, we compare the baseline model with one consumer group ($\{\beta_{1,1}, \beta_{1,2}, \beta_{1,3}, \beta_{1,4}, \beta_{1,5}\} = \{1, 1, 1, 1, 1\}$) and with two consumer groups ({5, 5, 1, 1, 1} and {1, 1, 5, 5, 5}). The velocity values of features one and five in the baseline model with different consumer groups are significantly larger than with the homogenous consumer group, which indicates that the velocity of product evolution increases when the heterogeneity of consumers increases.

TABLE 2. PRODUCT EVOLUTION VELOCITY[1] AND THE NUMBER OF REVEALED FEATURES[2] FOR HYPOTHESIS 1

	Feature 1	Feature 2	Feature 3	Feature 4	Feature 5	No. of revealed features
Producers innovation routine (0.33, 0.33, 0.34)	1.942	1.934	0.405	0.402	0.433	3.027
Baseline model	2.032	2.055	0.373	0.408	0.379	3.160
Difference	0.090***	0.121***	-0.032	0.006	-0.054*	0.133***
Statistical significance Pr(T > t)	0.004	0.000	0.086	0.399	0.013	0.001

1 Average of the max. values of each feature in the final period, $\frac{1}{N}\sum_{n=1}^{N} \max\{a_{s,1,t_{max}}, a_{s,2,t_{max}}, a_{s,3,t_{max}}, \dots, a_{s,m,t_{max}}\}$

2 Average of the number of revealed features($a \geq 1$) in the final period, $\frac{1}{N}\sum_{n=1}^{N} \text{count}_{\text{total Spec}}$

* Significance level 5%, ** significance level 1%, *** significance level 0.1%

TABLE 3. PRODUCT EVOLUTION VELOCITY[1] AND THE NUMBER OF REVEALED FEATURES[2] FOR HYPOTHESIS 2

	Feature 1	Feature 2	Feature 3	Feature 4	Feature 5	No. of revealed features
Baseline model {1, 1, 1, 1, 1}	2.032	2.055	0.373	0.408	0.379	3.160
Baseline model {5, 5, 1, 1, 1} {1, 1, 5, 5, 5}	2.099	2.072	0.402	0.404	0.425	3.231
Difference	0.067*	0.017	0.029	-0.004	0.046*	0.071
Statistical significance Pr(T > t)	0.035	0.320	0.092	0.428	0.018	0.052

1 Average of the max. values of each feature in the final period, $\frac{1}{N}\sum_{n=1}^{N} \max\{a_{s,1,t_{max}}, a_{s,2,t_{max}}, a_{s,3,t_{max}}, \dots, a_{s,m,t_{max}}\}$

2 Average of the number of revealed features($a \geq 1$) in the final period, $\frac{1}{N}\sum_{n=1}^{N} \text{count}_{\text{total Spec}}$

* Significance level 5%, ** significance level 1%, *** significance level 0.1%

TABLE 4. PRODUCT EVOLUTION VELOCITY[1] AND THE NUMBER OF REVEALED FEATURES[2] FOR HYPOTHESIS 3

	Feature 1	Feature 2	Feature 3	Feature 4	Feature 5	No. of revealed features
Baseline model	2.032	2.055	0.373	0.408	0.379	3.160
β_{inter}=1	2.105	2.063	0.404	0.427	0.405	3.236
Difference	0.073*	0.008	0.031	0.019	0.026	0.076*
Statistical significance Pr(T > t)	0.0211	0.5881	0.077	0.1945	0.1168	0.0430

1 Average of the max. values of each feature in the final period, $\frac{1}{N}\sum_{n=1}^{N} \max\{a_{s,1,t_{max}}, a_{s,2,t_{max}}, a_{s,3,t_{max}}, \dots, a_{s,m,t_{max}}\}$

2 Average of the number of revealed features($a \geq 1$) in the final period, $\frac{1}{N}\sum_{n=1}^{N} \text{count}_{\text{total Spec}}$

* Significance level 5%, ** significance level 1%, *** significance level 0.1%

In table 4, we find that the velocity of product evolution increases when the complementarity between product characteristics increases. The velocity values of feature one in the baseline model where product features are fully interconnected ($\beta_{\text{inter}} = 1$) is significantly larger than in the baseline model where product features are fully independent. Furthermore, the complexity of the product is inclined to increase when the complementarity between product characteristics increases.

VI. SUMMARY AND DISCUSSIONS

This study uses ABM to elucidate the logic of product evolution, which is affected by the producer's routine, consumer's preference, and complementarity of product features. We identify that the velocity of product evolution increases when the heterogeneity of producers or consumers and complementarity between features increase.

We draw the following implications based on the results. In respect to policy, we see the need to create a favorable environment for heterogeneous producers to participate in the market to enhance their competitive ability. Moreover, since the heterogeneity of consumers affects the velocity of product evolution, we see the need to pay attention to the technology-push model. As a result, we can create a favorable social environment for heterogeneous consumers. In respect to product development strategy, we see the need to focus on highly complementary technologies.

Future studies should consider other important factors that affect product evolution. Furthermore, as a forecasting tool that complements expert intuition, the next simulation model could be supplemented by additional case studies and simulation results.

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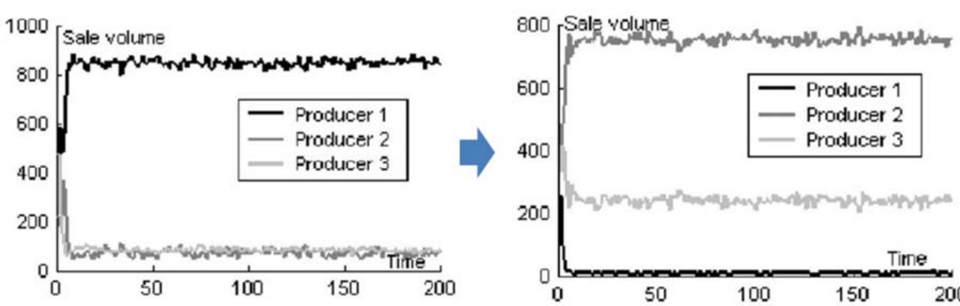
APPENDIX 1. THE BASELINE MODEL AND INITIAL CONDITIONS

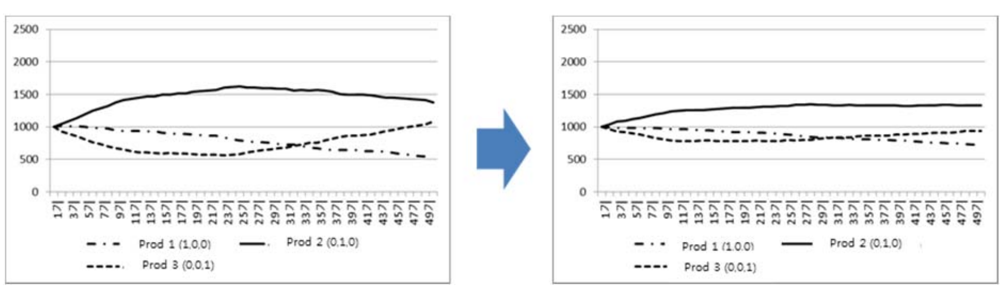
Simulation period : $T_{simulation} = 50$
Simulation repeat : $Rep_{count} = 1{,}000$
The number of firms : $N_{Firm} = 3$
The number of product types : $N_{product} = 3$
The number of firms changing their routines = 0
The changing range of radical innovation routine of firms, not the 1st seller. : $\Delta w_R = 0$
The changing range of incremental innovation routine of firms, not the 1st seller. : $\Delta w_I = 0$
The number of products evaluated by consumers : $N_{product,evaluated\ by\ consumer} = 3$
Initial product quantity of each producer : $N_{ProdQuanInit} = 1{,}000$
Total number of product technologies (features) = 5
The number of initial product's technologies = 2
The incremental value when innovation happens = 1
The maximum value of each technology of initial product = 1
The number of consumers : $N_{consumer} = 3{,}000$
The number of consumer groups : $N_{group\ of\ consumer}=1$
The consumer's percentage of each consumer group (%) : $N_{percentage\ of\ consumer\ group1} = 100$
The minimum time to copy the radical innovation : $T_{lag} = 5$
The succeed coefficient of radical innovation : $P_R = 0.05$
The succeed coefficient of incremental innovation : $P_I = 0.1$
The succeed coefficient of imitation : $P_C = 0.4$
The R&D investment of each producer : $I_{Firm\ 1} = I_{Firm\ 2} = I_{Firm\ 3} = 50$
The price of each product : $P_{Firm\ 1} = P_{Firm\ 2} = P_{Firm\ 3} = 1$
Weighted coefficient when radical innovation happens : $\beta_{wow} = 1$
The incremental coefficient of product output quantity : $C_{q_{Inc}} = 0.5$
The reduced coefficient of product output quantity : $C_{q_{dec}} = 0.5$
The added coefficient of interaction with each technology characteristics : $\beta_{inter} = 0$
Hedonic coefficients of each consumer group's technology characteristics:

$$\{\beta_{group1,spec1}, \dots, \beta_{group1,spec5,}\} = \{1, 1, 1, 1, 1\}$$

APPENDIX 2. VALIDITY TEST



(i) Comparison of heterogeneous consumers and homogeneous consumers; results of Ma and Nakamori model [3]



(ii) Consumer group sales compared with four consumer groups in our model