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How much can increase in expected product lifetime contribute to extending actual product use duration? A case study of refrigerators

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Abstract: The expected lifetime of a product is a consumer-oriented factor that needs to be considered when assessing product lifetime extension. While numerous studies have analyzed the expected lifetime of appliances, only a study for air conditioners has assessed the effect of changes in the expected product lifetime on the actual product use duration. Consequently, the impact for another product needs to be examined in order to develop appropriate product lifetime extension policies. This study estimated the impact of the expected product lifetime on the actual product use duration of refrigerators. We employed a dynamic discrete choice model (DDCM) to examine consumers' product replacement decisions as they are related to refrigerators. Also, we quantitatively analyzed the impact of the expected product lifetime on product use by using the parameters of the DDCM. The results showed that an increase in the expected product lifetime of refrigerators can contribute to prolonging actual product use for refrigerators. If the expected product lifetime is extended by 1, 2, and 3 years, the actual product use duration can be extended by 0.52, 1.05, and 1.59 years, respectively, which are shorter than the estimates obtained for air conditioners in a previous study. The results imply that the degree of product lifetime extension differs between products. Therefore, clarifying factors which causes the difference in the product lifetime extension effects is important to achieve product lifetime extension effectively.

Introduction

Transition to a circular economy is a major component of a sustainable society. Extending product lifetimes is one of main ways by which a circular economy can be achieved. To extend product use, the new circular economy action plan proposes that products have improved durability, reusability, upgradability, and reparability, and can be remanufactured, and that single-use and premature obsolescence should be avoided (European Commission, 2020). These EU principles appear to be based on a producer-oriented perspective. On the other hand, product replacement and disposal are not only affected by physical aspects such as product malfunction, but also by consumer preferences. To achieve product lifetime extension in a circular economy, it is important to consider consumer-oriented factors related to the product lifetime, product replacement, and product disposal.

One such consumer-oriented factor is the expected product lifetime, which has recently received considerable interest. The expected product lifetime refers to the consumers' expected product lifetime, and the gap between the expected and actual product lifetimes can be recognized as the product lifetime extension that could potentially be achieved. Previous studies have examined the length of the expected product lifetime for a variety of goods in different countries (Cooper, 2004; Lyndhurst, 2011; Cox et al., 2014; Oguchi et al., 2015; Wieser et al., 2015; Echegaray, 2016; Hennies and Stamminger, 2016; Woidasky and Cetinkaya, 2020).

It can be easily imagined that if the consumer's expected product lifetime is enhanced, actual product use duration will also be extended. However, this relationship between actual and expected product lifetimes is still vague and the impact of an increase in the consumers' expected product lifetime on actual product use duration have not been extensively studied. One of the few such studies is that of Nishijima and Oguchi (2020), who estimated the impact of the expected product lifetime in extending the actual product use duration of air conditioners using a dynamic discrete choice approach. That study showed that enhancing the expected product lifetime can contribute to extending actual product use duration.

The impact of the expected product lifetime on promoting longer product use may differ between products. Even if the consumers' expectation of product lifetime is enhanced, longer product use cannot be sufficiently achieved due to other factors that affect product replacement or disposal. It is therefore important to analyze the impacts of the expected product lifetime on actual product use for a variety of durable goods. Clarifying whether, and how much, an increase in the expected product lifetime promotes the extension of product use is considered to be beneficial for developing effective policies for extending product lifetimes in a transition to a circular economy.

This case study examined whether increases in expected product lifetime can extend actual product use duration for products other than air conditioners. We compared the impact of the expected product lifetime on actual product use duration in refrigerators with that of air conditioners. We also discuss how product lifetime extension should be considered for different durable goods.

Methodology and Data

Dynamic discrete choice model of product replacement decisions for refrigerators

This study employed a dynamic discrete choice model (DDCM), which is an econometric model that can be used to quantitatively analyze consumers' decisions in a forward-looking manner by considering product replacement decisions as they relate to durable goods (Rapson ,1987; Schiraldi, 2011; Rapson, 2014). Following Nishijima and Oguchi (2020), we assume that a consumer i who owns a refrigerator decides in year t whether they will keep their refrigerator or replace it with a refrigerator that is newly sold in year t. The replacement decision is expressed as a binary variable $a_{i,t}$. The expression $a_{i,t}=0$ indicates that consumer will keep their refrigerator, while $a_{i,t}=1$ indicates that consumer i will replace their refrigerator. When consumer i makes these product replacement decisions, they need to consider the following factors: annual electricity consumption of their current old refrigerator, $e_{i,t}^{old}$; annual electricity consumption of a new refrigerator sold in year t, $e_{i,t}^{new}$; the price of a new refrigerator sold in year t, $p_{i,t}^{ref}$; and the expected remaining product lifetime of their current refrigerator in year t, $EL_{i,t}$. Here, the expected remaining product lifetime is defined as the number of years that consumers consider that they can continue to use their current refrigerator from the time at which the decision was made. The utility functions for keeping and replacing their refrigerator in the DDCM, $u_{i,t}(a_{i,t}=0)$ and $u_{i,t}(a_{i,t}=1)$, respectively, can be described as follows:

$$u_{i,t}(a_{i,t}=0) = \delta_0 + \delta_1\left\{\log\left(e_{i,t}^{old}\right) - \log\left(e_{i,t}^{new}\right)\right\} + \delta_2 EL_{i,t} + \varepsilon_{i,t} \quad (1)$$

$$u_{i,t}(a_{i,t}=1) = \delta_3 \log\left(p_{i,t}^{ref}\right) + \varepsilon_{i,t} \quad (2)$$

where, δ_0, δ_1, δ_2, and δ_3 represent parameters of the DDCM, and $\varepsilon_{i,t}$ represents an unobserved error term.

Based on assumptions used in DDCMs in previous studies (Rust, 1987; Rapson, 2014), we express the probabilities of choosing keep and replace, i.e., $P(a_{i,t}=0)$ and $P(a_{i,t}=1)$, respectively, as a standard logit probability, as shown in equations (3) and (4) below.

$$P(a_{i,t}=1) = \frac{\exp\left\{u_{i,t}(a_{i,t}=1) + \beta EV\left(e_{i,t}^{new}, p_{i,t}^{ac} \middle| a_{i,t}=1\right)\right\}}{\sum_{\tilde{a}_{i,t}=0,1} \exp\left\{u_{i,t}(\tilde{a}_{i,t}) + \beta EV\left(e_{i,t}^{new}, p_{i,t}^{ac} \middle| \tilde{a}_{i,t}\right)\right\}} \quad (3)$$

$$P(a_{i,t}=0) = 1 - P(a_{i,t}=1) \quad (4)$$

where β ($0 \le \beta < 1$) is a discount factor and $EV_{i,t}$ is an expected value function in the DDCM. Based on the above probabilities, we can obtain the parameters of the model by maximum likelihood estimation. We applied a bootstrap method for checking the statistical significance of the obtained parameters. The number of the bootstrap samples was set to 200.

Estimated effect of a change in consumers' expected product lifetime on actual product use duration in refrigerators

Based on the obtained DDCM parameters, we can calculate the probability that a refrigerator of size class c which was newly purchased in year j ($j \le t$) is replaced in year t as follows:

$$\tilde{P}_{c,j,t} = \prod_{s=j}^{t-1} \left\{ P\left(a_{c,j,s} = 0\right) \right\} \times P\left(a_{c,j,t} = 1\right) \qquad (5)$$

This replacement probability implies that a consumer chooses keeping their refrigerator from year 0 (i.e., the year of purchase) to year $t-1$, and then chooses to replace their refrigerator in year t. Therefore, the replacement probability of a refrigerator is calculated as a joint probability of choosing keeping and choosing to replace their refrigerator as described in the equation (5)

If a consumer's total expected product lifetime is extended by ΔEL years, then the change in the expected remaining product lifetime can be reflected as follows:

$$EL_{c,j,t}\left(\Delta EL\right) = \begin{cases} \left(TEL + \Delta EL\right) - \left(t - j\right) & \text{if } \left(TEL + \Delta EL\right) \ge t - j - 1 \\ 0.5 & \text{if } \left(TEL + \Delta EL\right) \ge t - j - 1 \end{cases} \qquad (6)$$

where TEL represents a consumer's *total* expected product lifetime, which is the consumer's expected remaining product lifetime at the time of the new purchase (i.e., year j). This value is recognized as the consumer's expected product lifetime. A value of $t-j$ indicates the number of years of product use duration for the owned (old) refrigerator in the product replacement decision year. Setting the value of the expected remaining product lifetime as above, the replacement probabilities of a refrigerator can be calculated if the consumer's expected product lifetime is extended by ΔEL years. In this study, we refer to the case in which the expected product lifetime does not change (i.e., $\Delta EL = 0$) as the baseline case.

Data

To estimate DDCM parameters, we conducted a web-based questionnaire survey to assess the status of refrigerator replacement in Japan in 2019. The surveys were conducted in November 2019 and February 2020. Respondents were requested to provide the following information in the questionnaire survey: the model code of their current refrigerator; replacement cost of a new refrigerator; the number of years that the old refrigerator was used; whether they changed (or will change) the capacity of the refrigerator compared to their old refrigerator; and the expected remaining product lifetime of the old refrigerator. Using the model code of their current refrigerator, we can estimate the annual electricity consumption and capacity of the new refrigerators that respondents bought in 2019, or the old refrigerators that respondents kept in 2019. From the other questions, we were able to estimate the annual electricity consumption of old refrigerators among respondents who replaced their refrigerators in 2019, and the annual electricity consumption and replacement cost of new refrigerators among respondents who did not replace their refrigerators in 2019. We used the "Shinkyu-san" web application (Ministry of the Environment of Japan) to obtain annual electricity consumption data, and the "Kakaku.com" (Kakaku.com Inc.) website to obtain prices for various goods and estimate replacement costs. To estimate the impact of the expected product lifetime on actual product use duration, we also used those data sources. For the product price data, we used the median product price for each capacity class listed on the website on 15 November 2019.

We also set values of the total expected product lifetime TEL using information extracted from the questionnaire survey. Briefly, the median of the total expected product lifetime, which is the sum of the number of years of product use and the expected remaining product lifetime, was calculated as 15 years. Therefore, we set values of TEL in equation (6) as 15 years in this study.

Results

Table 1 shows estimation results of the DDCM parameters for refrigerators in Japan. Models 1 and 2 have different settings for the discount factor: $\beta = 0$ and $\beta = 0.9$, respectively. Signs of the parameters are all considered reasonable, in that the sign of the parameter of the expected remaining product lifetime is positive, and the parameter is statistically significant. This means that extension in the number of years of the expected remaining product lifetime increases utility of keeping the refrigerator. Therefore, if the expected remaining product lifetime is extended, the actual product use duration will also be extended due to an increase in the probability of consumers choosing to keep the refrigerator. Since a value of the log-likelihood in Model 1 is higher than that in Model 2, we used the parameters in Model 1 to estimate the impact of the expected product lifetime on the actual product use duration of refrigerators.

Parameters	Model 1	Model 2
Intercept δ_0	2.431*** (0.406)	2.216*** (0.479)
Annual electricity consumption δ_1	-1.926*** (0.210)	-1.758*** (0.257)
Expected remaining product lifetime δ_2	0.164*** (0.044)	0.171*** (0.043)
Price of new air conditioner δ_3	-0.267** (0.104)	-0.271*** (0.100)
Discount factor β	0	0.9
Log-likelihood	-622.750	-623.950
Number of observations	2690	2690

Bootstrap standard errors in parentheses.
***Statistically significant at 1% level

Table 1. Base estimation results of dynamic discrete choice model parameters

Figure 1 shows the impact of the expected product lifetime on actual product use duration of refrigerators using the parameters of Model 1, the log-likelihood of which is the highest among all models. The dotted line displays the product replacement probabilities for the baseline case in which the expected product lifetime does not change. The other three solid lines show the product replacement probabilities in cases where the expected product lifetime of refrigerators is extended by 1, 2, and 3 years. While the average product use duration of the baseline case is 12.3 years, those of cases if the expected product lifetime increases by 1, 2, and 3 years are 12.82, 13.35, and 13.89 years, respectively. Differences between the average product use duration of refrigerators in the baseline case and those of each of the expected product lifetime extension cases are 0.52 years for a 1-year extension of the expected product lifetime, 1.05 years for a 2-year extension, and 1.59 years for a 3-year extension. These results imply that if the consumers' expected product lifetime is extended, actual product use duration of refrigerators can also be extended.

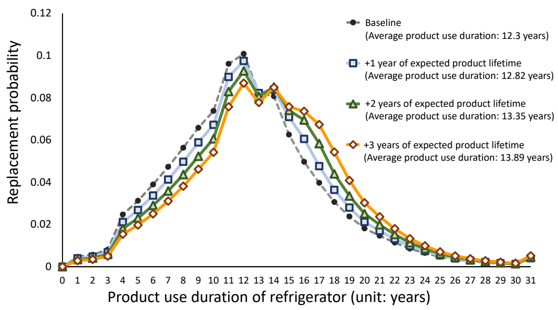

Figure 1. Replacement probability distribution of refrigerator estimated by dynamic discrete choice models

We also compared the results of the product use duration extension effects on the expected product lifetime for refrigerators with those of air conditioners, as estimated by Nishijima and Oguchi (2020). The replacement probabilities of air conditioners were calculated in a similar manner to that employed in this study. The product use duration extension effects of the expected product lifetime when extended by 1, 2, and 3 years for air conditioners were 0.9, 1.81, and 2.73 years, respectively. Comparing these values with those estimated for refrigerators in this study, the product use duration extension effect of refrigerators is less than that estimated for air conditioners.

Discussion and Conclusion

As in the case of air conditioners in Nishijima and Oguchi (2020), the results showed that increases in the expected product lifetime can extend the actual product lifespan of refrigerators. In this sense, products and services that enhance consumers' expectations regarding product lifetimes can indeed contribute to actual product lifetime extension for both air conditioners and refrigerators. However, we do not know factors affecting the consumer's expected product lifetime. It is therefore necessary to conduct a further analysis about what can extend the consumer's expected product lifetime.

On the other hand, the product lifetime extension effect of the expected product lifetime for a refrigerator is smaller than that of an air conditioner. Thus, the effectiveness of an increase in the expected product lifetime on product lifetime extension may not be the same for all products. This difference may come from differences in characteristics of those products related to product use or product replacement. Information on the differences is beneficial to conduct policy making more effective for product lifetime extension, we should clarify the characteristics of those products which cause the difference in the product lifetime extension effects of the expected product lifetime.

This study estimated the impact of the expected product lifetime on actual product use duration for refrigerators using a DDCM approach. The results showed that an extension in the expected product lifetime can contribute to product lifetime extension of refrigerators, but that the degree of product lifetime extension is smaller than that in a case of air conditioners. Since the contribution of the expected product lifetime on extending actual product use duration is expected to differ between products, implementing uniform policies for all durable goods is an inefficient means of extending product use. Rather, differences in the degree of the effect of the expected product lifetime related to differences in the characteristics of products need to be considered. We should therefore develop policies that facilitate sufficient product lifetime extension for specific product types in ways that consider the characteristics of those products. Such policymaking efforts will also create a variety of business models that will promote the extension of product use, which will reinforce economic competitiveness in a circular economy.

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