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A New Eco-Design Strategy to Assess Sustainable Environmental Innovations

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Abstract
This paper analyzes and discusses the potential role of evolutionary theories in environmental innovation with emphasis on sustainability. The study focuses on the dynamic mechanisms driving the adaptation of products to their changing environments. As a result, a strategy, called the Eco-evolution, is proposed. Eco-evolution is a strategy based on incremental innovation through re-examination of existent knowledge and technological trajectories. The strategy attempts the identification of lock-in of non-optimal technologies and sustainable alternatives, in order to outline the sustainable design and organizational horizons. To illustrate the practical application of the strategy, an example on domestic refrigerators is included. The study concludes that eco-evolution is efficient when identifying non-optimal technological trajectories and sustainable options for innovation on the base of existent knowledge.

1. Introduction
In light of sustainability, the focus of environmental policies and strategies has progressively shifted toward the product-service interface in which social needs and wants are to be met within societal and environmental limits. Recent theoretical studies on innovation indicate that sustainability requires of systemic transformations beyond the solely improvement of products and their environmental performance [1]. However, innovation tools such as eco-design are often restricted to product-related improvements due to cost and functional constraints [2]. Thus, there is an increasing need for new strategies to approach the challenging development of sustainable systems. Such strategic approach implies the understanding and re-consideration of the dynamic socio-economic structure [3]. In this context, an innovation process must focus on the dynamic adaptation of functions to evolving societies, their achieved knowledge and technological trajectories [4]. A dynamic adaptation in a context-dependent innovation pattern implies the adoption of evolutionary theories as a conceptual framework. It has been indicated that evolutionary theories support the analysis and understanding of concepts such as dematerialization and eco-efficiency. The evolutionary approach links changes in the material flow to long-term runs, uncertain growth paths, transformation in the sectoral structure, technological innovation and changes in consumer preferences [4]. Thus, evolutionary theories provide an adequate framework to analyze the shift of contemporary production-consumption patterns toward sustainable development.

This paper analyzes and discusses the potential role of an evolutionary strategy in the emergent field of environmental innovations. The study includes the outline of necessary concepts and antecedents, the description of the eco-evolution strategy and an example of its application on Japanese domestic refrigerators.

2. Background
All industrial activity is a response to social needs and wants. Individuals and societies have different necessities that are influenced by their values, goals, lifestyle and age – in other words – by cultural, psychological and physiological factors [5]. The satisfaction of these requirements, basics or superfluous, occurs at different spatial scales from individual to societal level. As scales become larger, the complexity of the productive system increases [5]. Because there are numerous aspects and many levels of motivations and constraints involved in the relationship between society and industry, the forces that drive the needs for products or services are a
2.1. Sustainable development

Nowadays the debate on environment focuses on the need to address the interrelated challenges of building sound societies, economies and environment. Such a premise called sustainable development, compases a series of initiatives, discoveries and events that are the roots of our current perception of environmental and social development. Most interpretations of sustainability lie on the connections between actions and effects in the environment, economy and society. Therefore, sustainability implies fulfilment of social needs in a different way as we presently do. sustainability emphasizes on those decisions and actions that determine how products and services reciprocally meet the requirements of consumers, the expectative of producers as well as the demands in the product development process. Such a concept is conceived at the backdrop of human needs, between production, the environment and society. Thus, the product development process is to be redefined in accordance with the general goals of the firm. The philosophy behind this new norm focuses on how and where to integrate all environmental demands in a product development process. ISO TR 14062 is aimed at shifting current product development strategies towards sustainable development while comprising tendencies that in the long-run are intended to transform the habits of consumption and the value of the different types of products from industrial to domestic use.

2.2. Environmental innovation at the product development process

Literature describes over 20 different methods specifically developed to address environmental demands in the product development process. Such methodologies, often defined as eco-design, vary on complexity and quality and they cannot be applied in every situation or stage during the development process [3]. In general, eco-design tools are developed to improve specific deficiencies in the environmental performance of products [7]. In addition, it has been indicated that cost and functionality are important constraints for environmental innovations [6]. To avoid restrictions, it has been proposed that innovations should be conducted as early as possible during the design process since a major design freedom is allowed [8] [7] [6].

Regarding successful experiences in eco-design implementations, there are five common principles [9] [6] that –in theory– are required to succeed while introducing environmental innovations in the product development process: 1) the ‘life cycle thinking’, 2) the eco-design process, 3) tools and methods, 4) the eco-design strategy and, 5) the Dialogue and partnership. The first principle represents the balance of impacts between life cycle stages to avoid design decisions that could relocate impacts from one stage to another. The second is the systematic consideration of environmental innovations during the product development process in a firm. Tools and methods, on the other hand, is the principle of combining existent eco-design tools and methodologies with enough flexibility and detail to assess the design process in a constant innovation scheme. The third principle emphasizes on the combination of complex constraints for environmental innovations [6]. To avoid this principle advocates the active dialogue between all actors and entities involved in the innovative process.

At sectoral level, several initiatives have been taken in order to establish standards procedures to assess the integration of environmental demands in the design process [10]. In this context, the most recent initiative is the ISO TR 14062 [10] published in November 2002, under the title: 'Environmental Management --Integrating Environmental Aspect into Product Design and Development'. The philosophy behind this new norm focuses on how and where to integrate all environmental demands in a product development process. ISO TR 14062 is aimed at shifting current product development strategies towards sustainable development while comprising tendencies that in the long-run are intended to transform the habits of consumption and the value of the different types of products from industrial to domestic use.

2.3. The concept of sustainable product development

In 1997, the Environmental Program of United Nations proposed a novel concept to address sustainability in product development. The "Sustainable Product development (SPD) is a concept that has been introduced to reconsider the relations between production, the environment and society. The concept is conceived at the broad field of human needs, technological and economic instruments that the satisfaction of needs implies." [7]. Thus, the product development process is to be redefined in accordance with availability of resources, environmental carrying
capacity and time-related distribution of resources. In this context, the reciprocal adjustment of product-related characteristics and the reinterpretation of societal needs are provided by the product functionality. The SPD concept broadly focuses on two features closely related to the product design; the cultural and the technological aspects of the product development process. The substitution between products and services responds to the idea of dematerialization where functions meet basic needs with fewer resources.

2.4. Indicators of Sustainability

In the beginning of 1990's a concept called Factor 4, developed by Ernest Von Weizsäcker at the Wuppertal Institute, constitutes the primary attempt on translating the sustainable development concept into a qualitative benchmark. The concept was based on the idea that over a span of one generation (25 years) it is reasonable to double the average living standard within the European Community, while simultaneously reducing the necessary amount of resources to meet that standard by 50% [11]. Afterward, as further conceptual development of factor 4, a new indicator factor 10 was introduced. Factor 10 implies that, on average, human impact on environment should be reduced by 50%, if at the same time the Western life standard is extended to the total world's population and the current production technology becomes ten times more efficient [11].

The philosophy behind factors 4 and 10 is the dematerialization [12] of production and consumption in which all needed products and services as well as energy demands are to be met with less resources. As a policy, dematerialization is aimed at influencing the development of economic systems in such a way that the environmental impact of the material flow caused by those systems is significantly, and in absolute terms, reduced [12].

The strategy to reach a factor 10 lies on an integrative approach to the productive system [11]. Such an approach requires at least the optimization of existing systems, new energy conversion technologies, efficient use of materials in the design process, new technologies to replace existing product functions, the organizational shift to provision of services and a new 'design thinking'. Although factor 10 entails a considerable reduction of the current level of pollution, some studies indicate that sustainability requires even higher efficiency. In this context, it has been proposed that a sustainable level can be achieved if in a fifty years-period the 95% of the total impact over the environment carried out by a productive system is reduced, in other words, if a factor 20 is achieved [13] [11].

On the other hand, in the contemporary literature, the eco-efficiency concept is often erroneously considered as a sustainability benchmark [11]. Although the term refers to an improvement of the ecological character of production while maintaining or improving economic profitability, this concept does not provide a measure for sustainability [11]. However, its approach is entirely compatible with factor 10 and 20 since eco-efficiency provides an operational concept that implies efficient use of nature to provide social welfare under profitable conditions. Moreover, the factors 10 and 20 provide the environmental goal against which the productive system must be adjusted to meet sustainability [11]. In addition, it is necessary to point out that eco-efficiency as well as factors 4, 10 and 20, are closely related to the concept of dematerialization [11] [12].

2.5. Environmental innovations at sustainable levels

Although the development of eco-design methods and tools has been partially motivated by the concept of sustainability, it has been demonstrated that the contemporary approach of eco-design broadly focuses on product improvement, a practice that in fact does not satisfy the requirements of sustainability [1] [6] [7]. Figure 1 illustrates the levels of eco-efficiency for a given innovation against a benchmark of sustainability,
The innovation of products and services is a dynamic response to evolving societies, their achieved knowledge and technological level of development. From an environmental perspective, innovation and changes in consumer preferences have been used to explain dynamic processes in economics. From an environmental perspective, the application of evolutionary theories has been proposed as strategic support in the analysis and understanding of concepts such as dematerialization and industrial ecology. The evolutionary approach links changes in the material flow to long-term trends, uncertain growth paths, transformation in the sectoral structure, technological innovation and changes in consumer preferences. Regarding sustainable development, evolutionary theories provide an adequate framework to analyze the shift in complex production-consumption trends.

In the innovation process, evolutionary theories have been used to explain the role of technological development in the adaptation of products and services to dynamic environments. In the evolutionary perspective, innovation can be either incremental or radical. In an incremental process, innovations are driven by imitative implementation of technologies. Innovation is then commonly associated with quality improvement of existing processes, products or services. Radical innovations, on the other hand, are discontinuous events, generally resultant from deliberate R&D and the consequent generation and flow of new knowledge. Although radical innovation is fundamental for the generation of new knowledge, it has been indicated that the improved use of the existent knowledge - the creative imitation - is more important for the development of economic systems. The evolutionary approach to innovation is particularly useful when determining the lock-in of non-optimal technologies in innovative trajectories that generates unnecessary social and environmental costs.

Overall, an evolutionary approach to environmental innovations provides the logistic framework to observe adequately the dynamism at the product development process and its potential link with sustainability.

3. The Need for a Evolutionary Approach in Environmental Innovation

The innovation of products and services is a dynamic response to evolving societies, their achieved knowledge and technological level of development. All elements and actors concerned in the socio-economic system co-evolve to adapt to their environments in a context-dependent motion that never reaches a static equilibrium. For more than hundred years, mechanisms driving the biological evolution such as selection-through-competition and adaptation have been used to explain dynamic processes in economics. From an environmental perspective, the application of evolutionary theories has been proposed as strategic support in the analysis and understanding of concepts such as dematerialization and industrial ecology. The evolutionary approach links changes in the material flow to long-term trends, uncertain growth paths, transformation in the sectoral structure, technological innovation and changes in consumer preferences. Regarding sustainable development, evolutionary theories provide an adequate framework to analyze the shift in complex production-consumption trends.

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Overall, an evolutionary approach to environmental innovations provides the logistic framework to observe adequately the dynamism at the product development process and its potential link with sustainability.

4. Proposal

Based on the analysis of the precedent referential background, we want to propose a strategy with an evolutionary approach to innovation. This chapter introduces and describes the most relevant characteristics of the proposal called Eco-evolution (EV), in a theoretical and practical context.

Considering the sustainable product development concept as a referential foundation, our proposal also reinforces the importance of "the relations between production, the environment and society" and focuses on "the broad field of human needs, technological and economic instruments that the satisfaction of needs implies". Therefore, the sustainable delivery of functions is to be considered the focus of innovation. In this context, environmental demands are translated into a need for sustainability in long-term horizons. Therefore, such demands are to be met in line with dematerialization of production and consumption. The innovative process, on the other hand, is conceived as a dynamic adaptation to interrelated changes in the structure of the socio-economic system (co-evolution). Cultural and technological trends are considered as the drivers of innovation. As a process, innovation will be incremental and based on the re-examination of existent knowledge and technological trajectories. Since the evolutionary approach to innovation implies incremental adaptation at system level, sustainability is to be compared against a factor 20 benchmark, as it is suggested in the Brezet model of innovation (Figure 1).

As an iterative process, the strategy consists of three phases or steps (Figure 2). The first phase, denominated knowledge trajectory, aims the compilation and analysis of information about a)
technical, b) cultural and, c) environmental aspects concerning the current product and system. Technical aspects include the product profile, the product life cycle, design evolution, technological development and life cycle cost. Cultural aspects to consider are the regulatory framework, the market and, trends on consumer's preferences and requirements. Aspects regarding environmental issues are resumed in a life cycle assessment and its further analysis. The resultant knowledge trajectory is translated into a set of tasks for efficient delivery of function in line with dematerialization.

At the second phase - the incremental innovation - the set of tasks is analyzed in order to identify lock-in of non-optimal technologies and to generate innovation options. The proposal for innovation constitutes a potential horizon for the design evolution. Such a result is denominated incremental innovation.

In the third phase, the trajectory examination, the incremental innovation is evaluated against the sustainability benchmark in order to verify the potential level of improvement or Eco-evolution. In order to perform the analysis, a single indicator is proposed:

\[ EV = EP - IEP \]  

Where:

- \( EV \) = Eco-Evolution
- \( EP \) = Current Environmental Performance of Product = 1;
- \( IEP \) = Improved Environmental Performance of Product:

\[ IEP = \left( \frac{\sum I_1}{n \times 100} \right) \]

Where:

- \( E_i \) = Potential Environmental Improvement rate in a given impact category i (%). Combining (1) and (2) \( EV \) becomes:

\[ EV = 1 - \left( 1 - \frac{\sum E_i}{n \times 100} \right) \]

The value of the \( EV \) indicator fluctuates between 0 and 1. \( EV=1 \) for example, indicates that environmental impact categories identified during the initial life cycle assessment are reduced by 100% in the proposed innovation strategy. However, the theoretical level of sustainability in accordance with factor 20 implies that the total impact carried out by the system is reduced by 95% [11]. Consequently, \( EV \geq 0.95 \) corresponds to a sustainable level of innovation if chosen impact categories are representative of the overall system’s impact. If the value of \( EV \) does not satisfy the benchmark, further analysis at the second phase of the strategy will be required.

If the assessment results satisfactory, a final engineering process aiming managerial matters such as cost control and product marketing will be conducted prior to final implementation.

5. Example of Application on Japanese Domestic Refrigerators

Phase 1 - Technical aspects [15] [16]: In general, refrigerators are classified as large domestic appliances. Their primary function is food preservation via mechanistic refrigeration. Refrigeration entails the process of removing heat from an area or substance in a controlled space in order to reduce the temperature of the system. A refrigerator is composed by four basic structural units: 1) refrigeration, 2) cabinet, 3)
insulation, and 4) control. The refrigeration unit provides the mechanical system for removal and transference of heat from the cabinet unit that provides the area for storage. The insulation unit prevents the flow of heat back to the cabinet. The temperature in the cabinet is regulated by the control unit via modification of the refrigeration cycle. All structural units include several components (Table 1). On average, the lifespan of a refrigerator is about 10 years.

The average material composition of Japanese domestic refrigerators [15] is depicted in Table 2.

The adoption of design innovations in Japanese refrigerators has broadly focused on changes in the population's lifestyle [17]. This has lead to focus innovation on storage capacity (volume), energy consumption, number of doors, specialization of inner compartments and, differentiated refrigeration cycles for cooling, freezing and chilling. Figure 3 resumes the design trajectory during the last decades [15].

Cultural Aspects: Approximately 4,331,000 end-of-life refrigerators are annually discarded in Japan. Because traditional disposal methods such as landfill and incineration lead to considerable environmental impacts, in the year 2001, the Japanese government enforced a law for collection and recycling of home appliances including domestic refrigerators [18]. The law encourages recycling and reuse of recovered materials and energy. The recycling rate for refrigerator is 50%. Producers are requested to collect and recycle their products, and to adjust the product development process in order to achieve a high-value recycling process. On the other hand, consumers are requested to pay the necessary fees for collection and recycling. Fees for collection vary between 2,500 and 5,000 yens. The recycling fee is 4,600 yens.

Table 1 Structural division of a domestic refrigerator

<table>
<thead>
<tr>
<th>UNITS</th>
<th>MAIN COMPONENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigeration</td>
<td>Compressor, Evaporator, Condenser, Valves, Pipes, Refrigerants (CFCs)</td>
</tr>
<tr>
<td>Insulation</td>
<td>Plastic Foam</td>
</tr>
<tr>
<td>Cabinet</td>
<td>Doors, Glasses, Containers, Temperature Exchangers</td>
</tr>
<tr>
<td>Cycle/Temperature</td>
<td>Heaters, Sensors, Controls</td>
</tr>
<tr>
<td></td>
<td>Electronics, Panels/Motors</td>
</tr>
</tbody>
</table>

Table 2 Average material composition of Japanese domestic refrigerator

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>MASS RATIO (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron and Fe-Ni alloy</td>
<td>49.0</td>
</tr>
<tr>
<td>Copper and Cooper Alloy</td>
<td>3.48</td>
</tr>
<tr>
<td>Aluminum and Aluminum Alloy</td>
<td>1.10</td>
</tr>
<tr>
<td>All Plastics</td>
<td>43.3</td>
</tr>
<tr>
<td>Polytetrafluoroethylene (PTFE)</td>
<td>(16.70)</td>
</tr>
<tr>
<td>Polystyrene (PS)</td>
<td>(11.39)</td>
</tr>
<tr>
<td>Acrylonitrile-Butadiene-Styrene (ABS)</td>
<td>(7.830)</td>
</tr>
<tr>
<td>Polyvinyl Chloride (PVC)</td>
<td>(3.420)</td>
</tr>
<tr>
<td>Others</td>
<td>(10.79)</td>
</tr>
<tr>
<td>Refrigerant Oils and Oil</td>
<td>1.20</td>
</tr>
<tr>
<td>Others</td>
<td>0.70</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100</td>
</tr>
</tbody>
</table>

Another regulatory policy concerns the total elimination of CFC refrigerant gases contained in the compressor (refrigeration unit) and plastic foams (insulation unit) that contribute to the depletion of the ozone layer [18].

Through operation, a refrigerator requires large amounts of energy. Such consumption rate represents, on average, 17% of the total electric energy consumed by Japanese householders [15]. Consequently, refrigerators were included in the Energy Conservation Law, as a designated product for the Top Runner Program. Such a program considers the energy performances of the most efficient products supplied for domestic use to set up the next efficiency standard [18].

Domestic refrigerators have a high diffusion rate of about 99.2% among Japanese consumers. The ownership rate is approximately 1,281 units per householder [15]. The current Japanese market for
refrigerators covers four segments [15]: 1) small-size models up to 120 liters (30%), 2) medium-size models between 121 and 301 liters (12%), 3) big-size model over 301 liters (33%) and, 4) extra-large-size models over 400 liters (25%). However, due to changes in demographic patterns, the market presents a bipolarization characterized by a high demand for small and large-size models [15] [17]. In addition, changes in lifestyle and dietary habits have also influenced the trend on requirements. In this context, there is an increasing demand for secondary functions such as chilling and long-term freezing modes [15].

Consumers broadly focus on price as the main criterion when purchasing a new product [17]. Therefore, environmentally-friendly products, often more expensive than standard products, are a secondary option among consumers. However, the demand for such products is expected to increase as well as the interest on alternative value-added services such as leasing or rental [15].

**Environmental aspects:** Several environmental impacts occur throughout the life cycle of a refrigerator. However, among life cycle stages, the major environmental burdens take place during the usage and material extraction phases [20] [15]. Table 3 summarizes a life cycle assessment (LCA) for an average Japanese domestic refrigerator [20]. In total, the usage and material extraction stages account for 97% of all life cycle impacts [20].

Phase 2: The analysis of the knowledge trajectory indicates that energy efficiency through product operation have to be radically improved. Moreover, the reuse of components as well as increased recovery of valuable materials is needed in order to improve dematerialization. However, considering that the current Japanese end-of-life strategy is broadly focused on recycling, it is likely to assume a potential reuse rate of about 30%. Such a value can be translated in the reuse of key components in the refrigeration and insulation units. Therefore, focus is required on modularization, design for disassembly and material choice.

Regarding product functionality, it was estimated that secondary functions such as chilling and freezing requires more diffusion in future products. Such approach implies the improvement on refrigeration and insulation efficiency.

Considering the overall information, it was determined that two structural units of the product present lock-in of non-optimal technology. Such units are the refrigeration and the insulation, in which the compressor and the insulating foam, respectively, must be replaced.

Based on available information [16] [21], a set of options was determined. Table 4 depicts available technologies and their potential environmental improvement ratio (EI) by targeted impact categories.

### Table 3 Life cycle assessment outline for Japanese refrigerators

<table>
<thead>
<tr>
<th>Critical Life Cycle Stages</th>
<th>Impact Category</th>
<th>Relative Weight</th>
<th>Relative Value</th>
<th>Main Retrieved Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usage</td>
<td>Energy Consumption</td>
<td>47.6%</td>
<td>Refrigeration</td>
<td>Compressor</td>
</tr>
<tr>
<td></td>
<td>Air Pollution</td>
<td>14.2%</td>
<td>Emission</td>
<td>Refrigerant Charge</td>
</tr>
<tr>
<td></td>
<td>Greenhouse</td>
<td>26.5%</td>
<td>Emission</td>
<td>Blowing Field from Glass</td>
</tr>
<tr>
<td></td>
<td>Acid Rain</td>
<td>11.4%</td>
<td>Emission</td>
<td>Emission Fan</td>
</tr>
<tr>
<td>Raw Material Extraction</td>
<td>Material</td>
<td>5.20%</td>
<td>Cost</td>
<td>Compressor</td>
</tr>
<tr>
<td></td>
<td>Energy Consumption</td>
<td>1.1%</td>
<td>Cost</td>
<td>Energy Consumption</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Composite Life Cycle Impact</td>
<td>97%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 4 Available Eco-design alternatives for domestic refrigerators

<table>
<thead>
<tr>
<th>Subject Area</th>
<th>Innovation Case</th>
<th>Strategy</th>
<th>Emitted Impact Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor</td>
<td>Material</td>
<td>Component</td>
<td></td>
</tr>
<tr>
<td>Refrigeration</td>
<td></td>
<td>Technology</td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td></td>
<td>Technology</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td>Technology</td>
<td></td>
</tr>
</tbody>
</table>

Based on available information [16] [21], a set of options was determined. Table 4 depicts available technologies and their potential environmental improvement ratio (EI) by targeted impact categories.

Phase 3: Considering the EI values and related impacts categories indicated in Table 4, it was determined that available technologies present an EV between 0.84 and 0.92. Such score indicates that the technological trajectory for environmental innovation in domestic refrigerators presents a high potential for sustainability.

In further analysis, it was determined that the EV score can satisfy the sustainability benchmark (EV=0.95) if an eventual technological improvement
allows a higher level of reuse. A reorientation of the business strategy towards service intensification may provide the necessary elements for such event [19]. Among strategies, lease with intensive service is proposed as an optimal solution. It has been estimated that lease of home appliances [19] can reduce the total product life cycle cost by 5%, the generation of wastes by 50%, and it increases the net profit by 15%. Although, energy consumption trough operation increases by 5%, the total energy spent in the life cycle decreases. In addition, the goals and requirements of this strategy are in line with combined recycling and reuse [19].

6. Concluding Remarks

The study analyzed and discussed the role of evolutionary theories in the sustainable product development process. The analysis depicts the need to approach the innovation process as a dynamic and incremental adaptation to changing environments. Consequently, a strategy, called the Eco-evolution, was proposed. To illustrate the performance of such a strategy, an example of its application on domestic refrigerators was included. The study concludes that eco-evolution is efficient when identifying non-optimal technological trajectories and sustainable options for innovation on the base of existent knowledge.

7. References


