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Sustainable Product Design of Innovative Design Methods and Case Studies

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Abstract. Sustainable design is an important design strategy for people to establish a healthily developmental circular economy. With the development, product design fields have changed accordingly, many successful product designs were created for sustainable effects with innovative design methods, including the designs of end-of-life treatment, product life cycle, and product-service system (PSS). There were some design solutions in design cases ranging from product itself or offered services, and these sustainable product designs utilized existing or new skills and technologies, utilizing resources and materials which were manufacturable and maintained to benefit locally, to achieve benefits on the various aspects of sustainability e.g., social, environmental, and economic. Analyzing and evaluating these design methods applied in typical design cases, assisted to summarize effective design approaches and strategies in sustainable product design. Some values behind the design were thus recognized based on the evaluated criteria which were used to judge product quality. The findings indicated the relevant design interventions in response to the design solutions could influence to reach sustainability, thereby assisting designers and researchers to learn closely.

Keywords. Product Design, Sustainable Design, Innovative Design Method, end-of-life treatment, Product Life Cycle, Product-Service System

1. Introduction

In 1972, American designer Victor Papanek first proposed in his book called "Designing for the Real World" [1], he explained "Designers should abandon those fancy and useless products, make rational use of limited resources, and create new ideas for our world. Provide rational and responsible design." This view reflects the concerns about environmental and social resource issues. At that time, the global economy benefited from the development of some applicative new technologies, materials, and energies, but people did not realize that the results of the economic growth would harm nature environment. Until global natural disasters emerged, after suffering from natural disasters and environmental pollution, people began to rethink the relationship between people and nature, and between people and products. People began to gradually shift the traditional resource-dependent economy into a circular economic model that relies on ecological resources, and circular economy has been gradually promoted globally. Sustainable design has become an important design strategy for people to establish a

healthily developmental circular economy. With the development, product design fields have also changed accordingly, and many successful product designs were created in sustainable design. Our previous study [2] discussed the context that design works in the design industry have moved toward project work and more often collaborative multidisciplinary projects. Thus, the design work is to be characterized as project-based, fluid, and enhanced by design practices. In design education, requiring student designers recognize the characteristics brought by the changes with sustainable design development, and learn the increasingly innovative design methods and tools across various disciplines. This study was to analyze and evaluate the design cases, and to summarize innovative ideas and methods applied in sustainable product design e.g., the idea of end-of-life treatment, product life cycle design, and product-service system (PSS) design. To focus on analyzing the adopted ideas and approaches, those values thus were recognized based on the evaluated criteria which were used to judge product quality. The aim was to find what are the relevant design interventions in response to those design solutions, which could influence to reach sustainability.

2. Theoretical Background

Initially, sustainable design ideas came from the concept of sustainable development. In 1987, the World Commission on Environment and Development was established in the United Nations and studied the issue of "Our common future". The organization defined "sustainable development" for the first time as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Another definition came from Paul Hawken and presented the basic assumptions of the concept in an accessible way: "Leave the world better than you found it, take no more than you need, try not to harm life or the environment, make amends if you do" [3]. The ideas behind these are to achieve economic development and prosperity in human society and require people to maintain ecosystems and make rational use of natural resources. The concept of sustainable design was grounded in the development of our society, and it was interpreted as: it is a strategic design activity that combines products and services to create and develop sustainable solutions to meet the specific needs of consumers [4].

Three design methods can be proposed into design practice for sustainable product design, namely end-of-life treatment of products, product life cycle design [4], and product-service system (PSS) design [5]. For an example of the PSS design, sustainable innovation is around one idea of changing customers' behaviours, specifically, transforming can be created by considering how products are delivered and consumed. This is exemplified by applying the PSS design method. The idea behind this is that services offered by companies will be fulfilled with people's needs, but not products; the physical artifact of a product is not necessary to customers. By focusing on functionality, product designers are required to ask whether a tangible product is needed or whether it would be added with corresponding services, to raise environmental and social benefits from the PPS design.

For study purposes, some criteria by which we judged product quality were broader and built on environmental, economic, and social [6]. The successful sustainable product designs could be evaluated with the proposed criteria: need, suitability, usability, relative affordability, local manufacture, local control and repair, advancement, and

empowerment. With the criteria, the evaluated framework was structured for references (Table 1). The first set of factors is related to product itself; these reflect more approaches to products that focus on "user-orientated" ways of promoting social sustainability. The second set of factors is related to product design and production locally. The final set of factors is related to the use models, they demand diverse ways of doing things and thinking things, advancement is of adding new jobs and skills in corporations, and empowerment is to enable relevant community locally by design. The findings emphasized that the sustainable design progresses from product itself to production process, and to business model, and social sustainability become more service-focused versus user-focused.

Table 1. The evaluation framework with the criteria

Use models	Advancement: Dose it create jobs and skills in companies or communities?		Empowerment: Dose it empower people to own and develop the design solution?	
Process	Local manufacture: Can it be manufactured locally?	Local control: Can it be controlled and maintained locally?	Repairing: Can it be repaired and retrieved locally?	
Product	Needs: Do the users and the communities need it?	Suitability: Is it socially, culturally, and environmentally appropriate?	Usability: Is the solution easily understood and easy to use?	Relative Affordability: Is it accessible and affordable?

3. Innovative Design Methods and Case Studies

There were many cases of product design concerning sustainable design, some were more successful than others. These design solutions ranged from product itself or offered services, and the sustainable products utilize existing or new skills and technologies, resources, and materials, to benefit locally and its supply chains. Through exploring the applied approaches in these cases e.g., the idea of end-of-life treatment, product life cycle design, and PSS design, the interventions of the innovative design were learned closely.

3.1. The Idea of End-of-Life Treatment

The concept of end-of-life treatment refers to applying effective treatment technologies on emerging wastes at the end of product production or use process. This concerns the critical issues in developing environmental management strategies. Aiming at some possible damages from the specific products to the environment, the formulated feasible method is conducive to eliminating environmental pollution and slowing down the development of pollution and damage caused by product manufacture. This is an important design strategy. Initially, people understood the environmental pollution and damage issues, which caused people to worry about pollution effects, and thus noticed how the environment must be protected ecologically. Returning to products, "end-of-life treatment" mainly concerns how to make the emerging wastes reduce negative impacts on the environment at the end of a product's lifespan and think of the possible solutions to turn the wastes into treasure. For example, a way of combination strategy is adopted to extend product lifespan, which is utilizing the product parts design to increase the

possible flexibility of a product, i.e., the multiple functions design will address the product's parts to meet opportunities of various uses under different situations.

There are many related cases in daily life, e.g., dealing with discarded plastic bottles from the ideas of the Coca-Cola company and the water brand Evian. Plastic material is difficult to degrade. If the bottles are randomly thrown into the environment, it will cause a lot of pollution. Therefore, considering how to dispose of discarded bottles is a challenge that designers need to think about. Coca-Cola used the design of end-of-life treatment, aimed at utilizing discarded plastic to transform its bottles use into interesting and practical items, to encourage consumers to recycle beverage bottles. Specifically, by repurposing the useless bottles by creating special bottle caps, the finished plastic beverage bottles were turned into bubble makers for children to play with (see Figure 1, left), brushes for painting, and other uses.

Figure 1. The bottle redesign of Coca-Cola (left) and the recycled plastic bottles of Evian (right)

To compare with the method of Coca-Cola, Evian adopted a different way to approach discarded bottles. They released a kind of label-free bottle made of recycled plastic on a recycling solution at the end of the product lifespan. To implement a fully circular bottle design they challenged the industrial restrictions in technology and production. The recyclable 400-milliliter bottle was made of recycled polyethylene terephthalate (RPET) and featured an embossed logo instead of a label, see Figure 1, right. However, the pink cap was made from virgin high-density polyethylene (HDPE) and oriented polypropylene (OPP), i.e., these were approximately fully recycled.

Evian adopts a circular method with technologies for its plastic usage, where the production of plastic material will be kept within economy and out of nature, which means the bottles will be made from recycled plastic, whereby are retrieved at the end of the product's lifespan. Additionally, considering the works for local sustainability through empowering communities and applying advanced technologies, they collaborated with other units such as governments, recycling industry partners, and consumers over the world to increase collecting plastic bottles and recycling rates. For example, in the United States, they established a Closed Loop Fund which has developed large-scale recycling infrastructure. In Indonesia, it has worked with research partners to analyse waste captured by an interceptor technology which is a way of stopping plastic waste from entering oceans. Through collaboration with a variety of units, they have been keeping on supporting recycling solutions to ensure bottles were recycled suitably.

Cozy & Green is another case of utilizing the end-of-life treatment method to treat discarded bottles for cycling use solution. With the launch of their zero-waste shopping program, they created a mobile app-based service that offered a convenient way for

people to shop from refill stores. The service offline was established through they can pick up reusable bottles from customers, refill and deliver them to customers' doors. They found a lot of problems in this product delivery process with refill stores based on the research with customers, which mainly included a lack of refill and delivery services, inconvenience of the shopping experiences due to the extra effort, and difficulty to find nearby refill stores. For solving the problems, they created a mobile application that enables connecting local refill stores for making online orders for customers in the area. Based on the received information, their workers can pick up customers' bottles to refill and deliver them back to their homes.

They focused on utilizing reusable bottles and customers' needs for convenient shopping experiences. The online solution was created to suitably increase the convenience of shopping events. At the intersection of sustainability, retail, and technology, the app-based service was created to take on challenges with applied information communication technology (ICT), and out of zero-waste shopping, and achieved the sustainable product design with the evaluation framework, see Table 2.

Table 2. Evaluation of the mobile app-based service

Use models	Advancement: Created jobs and skills in the company, developing the training in the consumers.	Empowerment: Established the connection relationship among consumers, refill stores, and Cozy & Green.		
Process	Local manufacture: To produce the design with the provided service locally.	Local control: To maintain and develop the project with refill stores locally.	Repairing: No need of repairing and retrieving physical products.	
Product	Needs: The consumers who own environmental consciousness were strongly desired.	Suitability: These were appropriate among consumers, refill stores, and Cozy & Green.	Usability: Created a convenient way, this was easily understood and easy to use.	Relative Affordability: It was limited by the area's size. Need the relative web services in the areas.

3.2. Product Life Cycle Design

The product life cycle design is to carry out the design intervention from the source of product production to extend to product waste e.g., considering on raw material, manufacture technology, needs from different customers, etc., and these impacts required to consider in a product's lifespan with design strategy. The obtained design concepts can be implemented in real situations and achieve sustainable goals. Compared with the end-of-life treatment strategy that occurs after environmental pollution and waste, people realize that they should notice environmental protection in the beginning. Such an idea of post-pollution treatment is viewed as a remedial measure. People realize that the applied approaches after pollution cannot completely solve those environmental problems, thus proposing the method for products' life cycle. We must pay increasing attention to the idea of clean production at the beginning so that it is possible to minimize pollution and reduce environmental impacts during product production and use process. The strategy of a product's life cycle requires considering multiple factors at the source

for sustainability, i.e., approaching source control from the beginning. A loop process with the focus of the various stages is shown in Table 3.

Table 3. The stages focus on the product life cycle design

The stages	The focuses
Product planning stage	Need to consider clean, renewable, and non-polluting raw materials in the beginning.
Product production stage	A whole-process clean production method is adopted to avoid pollution and waste of resources.
Product use stage	Need to reduce environmental load to the maximum extent when using the product.
Product discarded stage	When a product reaches the end of its lifespan in service, the parts and materials can be reused to realize recycling use in the industry chain and form a sustainable production of garbage-free, pollution-free, and renewable.

In a design practice of bamboo furniture, regarding the life circle assessment theory, the study of Deng et al., (2023) proposed the process and strategy of sustainable product design as shown in Figure 2.

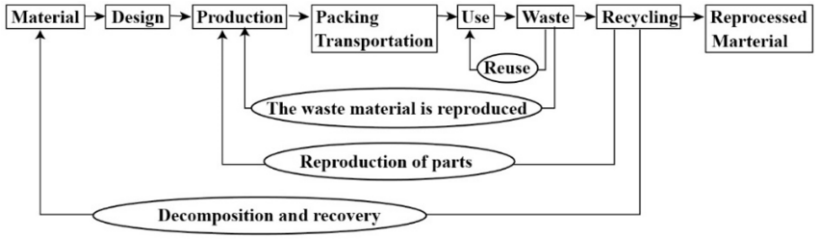

Figure 2. A sustainable product design process and strategy

One typical example of no waste and no pollution in product life cycle is from bamboo material products and the material itself. Bamboo has many advantages such as environmental protection, shorter growth cycle, higher yield, and higher strength. In this case, MOSO is an international company relying on the Chinese bamboo industry in the development of innovative and sustainable bamboo products. The range of products is divided into some product groups e.g., flooring and panels. They offered a natural, fast-growing alternative with the proven sustainable bamboo products based on publishing the environmental impacts of the bamboo products, i.e., some relative studies concerned Environmental Product Declarations (EPDs) and Life Cycle Assessment (LCA). More specifically, EPDs according to ISO 14025 standard (ISO, 2006c) nowadays is a well-acknowledged tool to communicate credible information about the environmental performance of a product based on an LCA study [7]. They are defined as "providing quantified environmental data using predetermined parameters and where relevant, additional environmental information." At that time, collaborating with the research institutes, they presented a full LCA study for partial bamboo products. With developing various verified EPDs for the product ranges reported the results about low environmental impacts in manufacture. Specifically, from the report of Laminated (EN15804), online documentation, involved the manufacture of the solid panel and beam regarding some visually appealing products. Stage A of the process involved disposing

of bamboo strips by gluing together and with a hot press way. These (in Table 4) were collected to evidently evaluate for environmental impact results.

Table 4. GB, GF, GL, and respective standard deviations (partial results)

EE	Unit	A1	A2	A3	A4	A5
GB	kg CO2 eqv.	-1.13E+3	4.29E-3	-1.08E+1	-4.75E-2	7.30E-1
GF	kg CO2 eqv.	9.57E+1	9.28E+0	2.00E+2	1.07E+2	2.92E+1
GL	kg CO2 eqv.	2.90E-2	3.40E-3	5.42E-2	1.14E-1	1.09E-2

EE: Environmental Effects, GB: Global warming potential - Biogenic, GF: Global warming potential – Fossil, GL: Global warming potential - Land use and land use change

In sum, through using the product life cycle design each phase of products' lifespan was involved, whereby the goal of eco-impacts could be reached. MOSO applied the product studies, as an effective way with the partners, to obtain the evaluated results where sustainability was proven within product production and achieved the sustainable product design with the evaluation framework, see Table 5.

Table 5. Evaluation of the MOSO bamboo products

Use models	Advancement: Created jobs and skills in the company, and its supply chains in the industry.	Empowerment: Empowered customers to achieve product applications with ecological and sustainable development.		
Process	Local manufacture: To produce bamboo products locally and their supply chains.	Local control: To manage and maintain the products locally.	Repairing: To repair and retrieve locally with a full recycling strategy.	
Product	Needs: Met the requirements of highest technical and quality standards, and from sustainable manufacture.	Suitability: Enabled the full life cycle of product safety, and well-being of people involved.	Usability: Provided the use of expertise and higher standards.	Relative Affordability: Offered to worldwide needs, with the backbone of the Chinese bamboo industry.

3.3. Product Service System (PSS) Design

With the development of sustainable design, designers and researchers have paid close attention to sustainable issues and environmentally friendly design, e.g., green design, low carbon, etc. Among them, the PSS design has received more notice because it has the characteristics of environmental protection, social and economic effects. What is a PSS design? According to the interpretation of the United Nations Environment Program in 2002, this can be understood as the result obtained by utilizing an innovative strategy under a new situation or context, e.g., a bike-sharing system is viewed as a typical PSS design. In this sense, the design focus is shifted from use-oriented product design to providing integrative products-service systems to meet people's needs better and effectively. The explanation highlighted such a shift in design from material products to non-material services. In other words, service design is an extension and expansion of

physical product design. It is a whole-process design based on material products, and the purpose is to provide users with high-quality product services. In daily life purchasing products means gaining a lot of corresponding services from product providers. For examples, we buy cars to intend automobile sales services and buy mobile phones for mobile communication services. Designing a specific product means the corresponding services are offered by the company. The ultimate purpose of consumers buying products is not to obtain the physical product itself but the services.

In product design practice, with such shift, the product-service design not only meets users' needs, but also complies with the sustainable developmental requirements of energy saving, environmental protection, and social harmony. Service design has emphasized a concept of shared consumption to enjoy services, that is, people enjoy services a certain product brought. Regarding the case of bike-sharing services, it is convenient to meet such a need for short-distance travel. Specifically, bike-sharing services meet the users' needs in traveling at the end of public transportation, and the "last mile" issue has been addressed by the service design, which is after public transportation people need to consider choosing either walking or taking a taxi to go home. When the services provided by some companies in China initially e.g., OFO, Hellobike, and Mobike, the number of their users had shown a blowout growth. These help users obtain services in a leasing way. Users only use mobile app-based services to register an account, pay a deposit, scan the code of a bike to unlock, and then get the bike with the related riding services provided by those companies.

To meet peoples' demands of bike-sharing services requires the companies to provide a mixed offer of both products and services so that sustainability regarding both consumption and production is possible. From a PSS and innovative design perspective, a bike-sharing system should offer a "use-orientated" approach to the ownership rights of the material artifact. The companies retained the ownership in this PSS configuration and the users purchased the use of the product/system over a given period or units of service. The companies created the product-service delivery system with the service delivery process grounded on ICT technology. In the bike-sharing industry, the service delivery design process was divided into two dimensions as: online and offline service operations [8]. Specifically, these bike-sharing operations were supported by applying mobile applications for the main two services of delivering the offline ride-sharing service for users and informing the company's employees about managing and maintaining bikes. The offline bike-sharing operations were regarded as the activities of bike-sharing operations procedures on the street, and the online bike-sharing operations were supported by the technical department which aimed to provide effective guidance to the offline bike-sharing operations. A created working diagram (see Figure 3) shows a basic bike-sharing operations process for the bike-sharing PSS design. With the organization of the emerging data including material and non-material, it facilitates our understanding of how the key elements interact, support, or conflict with each other during the system working, and could support the cross-analysis in depth.

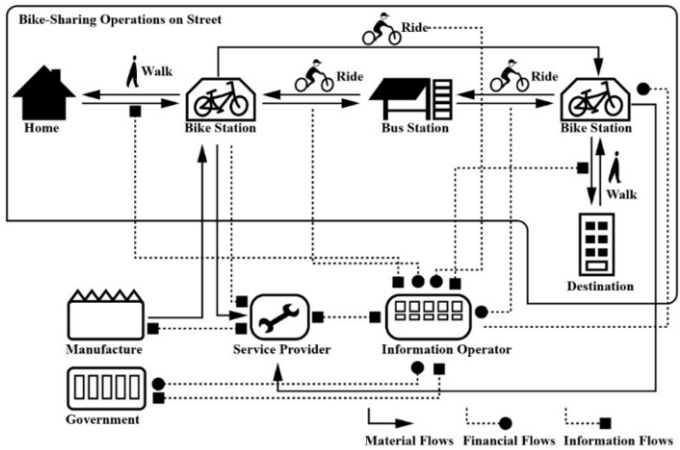

Figure 3. The working diagram of the bike-sharing operations system

In a typical case in Shanghai in 2016, the bike-sharing services in Shanghai saved 8358 tonnes of petrol and decreased CO_2 and NO_X emissions by 25,240 and 64 tonnes [9]. The study demonstrated the spatial distribution of environmental benefits of bike sharing, and indicated Hongkou district is the highest density of environmental benefits with the highest population density. For each square kilometre (km^2) in this district, bike sharing resulted in a reduction of 33 tonnes of petrol, 100 tonnes of CO_2, and 254 kg (kg) of NO_X in 2016 (Table 6), i.e., 35,000 people per km^2, bike-sharing in this district resulted in a decrease of 2.9 kg CO_2 emissions per person. Therefore, in this study bike-sharing services indicated it with great potential to reduce energy consumption and emissions to reach sustainability.

Table 6. Environmental benefits of bike-sharing services in Shanghai (partial results)

No.	District	Area (km^2)	Fuel (t)	CO_2 (t)	NO_X (t)	Fuel per unit area (kg/km^2)	CO_2 per unit area (kg/km^2)	NO_X per unit area (kg/km^2)
1	Baoshan	301	733	2214	5.6	2433	7348	19
2	Changning	37	409	1236	3.1	10,995	33,205	84
3	Chongming	1357	0	0	0	0	0	0
4	Fengxian	721	1	3	0	1	4	0
5	Hongkou	23	774	2339	5.9	33,087	99,921	254
…	…	…	…	…	…	…	…	…

Utilizing the bike-sharing PSS design which can facilitate people driving shared bikes in urban will be realized to the various aspects of sustainability. Driving bikes do not release greenhouse gases, unlike buses and cars. So, if people rent bikes from bike-sharing systems, driving bikes will reduce the carbon footprint and take measures to keep the environment safe. Moreover, the bike-sharing service delivery system can be utilized for producing economic benefits. For example, to meet people's increasing demands from these uses, participatory companies are required to guarantee that there are adequate numbers of shared bikes on the street. Thus, require the companies to spend a large amount of money to purchase many shared bikes, which the local bike manufacturers

will benefit from these, and the related providers in supply chains also will benefit from these e.g., making docking stations. Finally, people who use the service will decrease the frequency of using cars because they live near the bike-sharing docking stations, then, the use of shared bikes significantly alleviates traffic congestion there, whereby social efficiency will be improved. Then, various communities were provided bike-sharing services, thereby this also is viewed as applying the way of empowerment to achieve community construction and development. In sum, with advanced technologies the bike-sharing PSS design focused on users' need to provide shared product services. Through using the bike-sharing PSS system a potential transition emerged and engaged in low-carbon mobility in urban, i.e., the PSS system supported by the bike-sharing service delivery operations, users can freely use bike-sharing services without producing any emissions, thus, the bike-sharing PSS design achieved in sustainability with the evaluation framework, see Table 7.

Table 7. Evaluation of the bike-sharing PSS services

Use models	Advancement: Created jobs in the companies, and developing app-based services with the users.		Empowerment: Empowered people to engage in low-carbon transportation.	
Process	Local manufacture: To manufacture locally and their supply chains.	Local control: To manage and maintain the products locally.	Repairing: To repair bikes and retrieve the discarded bikes locally	
Product	Needs: Most people desired to use shared bikes for low-carbon transportation.	Suitability: These were appropriate to the uses of travel and commuting.	Usability: This is convenient to use with the app-based service.	Relative Affordability: Uneven distribution, the urban centres were usually over-supply but a limited number of in the suburban.

4. Conclusion

This paper contributed to the product design fields in general and provided case studies on exploring their design methods in response to sustainable issues. Through analyzing and evaluating the applied design approaches based on the evaluation framework, from the cases including the methods of end-of-life treatment, product life cycle design, and PSS design, then, the finding indicated that some relevant design interventions enable the design solutions to achieve sustainability in various aspects. Specifically, by way of end-of-life treatment, Coca-Cola took the repurposing strategy to the useless bottles by creating special bottle caps, the useless bottles thus became recycled use, and environmental benefits were reached. Evian and Cozy & Green also adopted the ways of end-of-life treatment. MOSO used the product life cycle design in its production, i.e., by presenting the EPDs reports where sustainability was proven in those products in manufactures. Further, by using the bike-sharing PSS design and the bike-sharing service delivery system, the bike-sharing companies considered and realized sustainable goals. For design practice, the paper could provide opportunities to learn innovative design methods with sustainable issues, these might inspire designers to think and identify the appropriate approaches which will be adopted for specific

sustainability challenges. In design education, educators could consider the approaches to sustainable issues with challenges in design courses, where the importance of teaching is to enable student designers to know the rich and complex concerned issues in contexts, and to explain how to use approaches individually to contribute to some sustainable developmental aspects.

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