

# A Framework for Locally-oriented Product Design Using Extended Function-structure Analysis and Mixed Prototyping

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## Abstract

Ensuring sustainable consumption and production (SCP) patterns is an important task and is one of the United Nation's sustainable development goals. Each SCP pattern needs to be appropriate for its target region, so they differ according to regional or local characteristics, including culture, climate and customs. Therefore, product design should take into account these characteristics as appropriate. The purpose of this study is to propose a framework for locally-oriented product design using an extended function-structure map and a mixed prototyping environment. The former is applied to identify local specific information related to product function structure and to generate design ideas, and the latter is applied to evaluate design solutions in a reconfigured living environment comparable with an actual one. Combining these two elements in the design process allows local information to contribute to the design of locally-oriented products. The usefulness of the proposed framework is shown by applying it to the development of an improved washing machine design for use in the Vietnamese living environment.

**Key words:** locally-oriented product, satisfier, sufficiency, sustainable consumption and production (SCP), sustainable design

## 1. Introduction

Realizing a sustainable society is the most challenging issue facing humanity today. Ensuring sustainable consumption and production (SCP) patterns is one of the United Nation's sustainable development goals (SDGs; UNEP, 2010). Product companies have focused on improving the efficiency of production and products from the perspective of the environment. Eco-design guidelines and methodologies based on life-cycle thinking have been developed (Brezet & Hemel, 1997; Chiu & Chu, 2012; Kobayashi, 2005). They have contributed to improved eco-efficiency of products, and indices of product eco-efficiency have also been developed and applied (Kobayashi et al., 2005).

The appropriateness of SCP patterns varies according to factors such as the culture, climate, lifestyle and social norms of the target region. Indeed, studies have pointed out that general differences in human nature can be explained by culture (Hofstede et al. 2010; see also Tasaki & Kojima (2021) in this special issue.), 2010) and climate (Watzuji, 1961), which affect individual personalities at a

deeper level. This evidence suggests that regional differences have a broad effect on the human nature of ordinary people. To achieve an appropriate SCP pattern in each region, one study identified the importance of focusing on local characteristics in product design (Kobayashi, 2015). To recognize local characteristics and generate ideas for locally-oriented products, the same study proposed the concept of an extended function-structure analysis method that visualizes the relationship between local specific information and a product function-structure map (FSM) (Kobayashi, 2015). Another study later developed a visualization system for the extended function-structure map (EFSM) (Sugita et al., 2017).

In contrast, SCP focuses on not only more efficient production and products but also on reduced consumption while satisfying human needs, which is referred to as "sufficiency" (UNEP, 2010). However, sufficiency has been discussed mainly in the context of sustainable consumption and consumer behavior (Hertwich, 2005; Jackson, 2005), and there are few studies in the field of product development. To improve sufficiency related to

industrial products in daily life, we proposed a framework based on the living-sphere approach (Kobayashi & Fukushige, 2018). An important aim of this approach is to realize satisfaction of basic human needs totally by products within the living sphere in order to design a locally-oriented sustainable product. An integrated framework of this approach consists of a universal human needs framework, as proposed by Max-Neef (Max-Neef, 1991), as well as the general concepts used in engineering design (Pahl & Beitz 1988). A key element of this needs matrix is the “satisfier,” which refers to a quality which satisfies basic human needs that are expressed in the natural language (Kobayashi, et al., 2019). A mixed-prototyping (MP) environment was established and applied based on the living-sphere approach to evaluate new ideas of locally-oriented design (Kano, et al., 2019). However, the EFSM and MP system have not yet been applied systematically.

The objective of this paper is to propose a framework for designing locally-oriented products through use of EFSM and MP environments. The remainder of this paper is organized as follows. Related works are summarized in Chapter 2. In Chapter 3, a framework using EFSM and an MP environment is proposed. An applied example is described in Chapter 4, and its importance and remaining issues are discussed in Chapter 5. Chapter 6 concludes the paper.

## 2. Related Works

Practical application of product development approaches have been carried out that consider local culture, geography, climate, geopolitics, history and educational practices. A popular “market-in” approach is field observation, in which a skilled local observer or analyst identifies a gap in the market in terms of price, infrastructure, required performance or user education level. Because field observation is independent of other techniques, it can be easily applied to product development in an emerging or developing country, although it is relatively expensive. Field observation is a basic element of locally-oriented product design. For example, one study has reported on observation of cultural contexts (Spencer et al., 2015). However, the success of field observation depends on the person who analyzes the cultural contexts.

To determine specific preferences of a product user, personas are applied in product development (Pruitt & Grudin, 2003). Each persona has a gender, age, race, ethnic, family and socio-economic background. It is effective for establishing the right persona while considering appropriate regional characteristics. Cultural context, however, not only consists of the traits or behaviors of individuals but is also found in and through the everyday activities of the population as a whole (Lee, 2012). Thus, methods centered on the individual,

including personas, carry the risk of overlooking invisible and implicit cultural values, thus providing incomplete and/or incorrect information to the designer. Co-design is regarded as a collaborative process between engineers and people in the local community. In a co-design approach, a workshop is held at each project milestone. A gatekeeper at each workshop plays the important role of connecting local residents with engineers (Sianipar et al., 2013). The quality of the design depends on the gatekeeper. A problem encountered in co-design is the difficulty of sharing information among project members, which can result in gaps in understanding.

Design evaluation is also an important process in product development. In terms of regional or cultural product design, most studies have applied a questionnaire approach (Hsu et al., 2013; Ghazali et al., 2018). Subjective evaluation using the semantic differential (SD) method (Osgood et al., 1957) is also applicable to cultural design. Principles for design in the developing world are useful in design review, but they are empirical and ad-hoc (Mattson & Wood, 2014). In past decades, various collaborative software applications based on virtual reality (VR) and augmented reality (AR) technologies have been developed to connect people and share design information in an immersive virtual environment (IVE) (Ong & Shen, 2009). Such VR- and AR-based applications for design review focus mainly on a target product designed with geometric modeling functions based on three-dimensional computer-aided design (3D-CAD) platforms (Feeman et al., 2018).

To review the design of industrial products, it is desirable to approximate the IVE to an actual space in which the designed products will be used. This enables experience with product-use cases in a variety of situations in their actual environment, and enables the designer to validate the functionality and visual harmony of the design with other products in the space. For this purpose, MP is an emerging approach in usability testing in a multimodal environment and is able to involve sight, hearing and touch in an IVE. This technology augments reality and the ability to analyze the inter-relationships between the physical form and behavior of industrial products (Bruno et al., 2010; Barbieri et al., 2013).

In summary, it would be desirable to have a holistic framework to collect and apply regional or local contextual information to facilitate the design and evaluation of locally-oriented products. However, such a framework has yet to be established.

## 3. Framework

The proposed framework for locally-oriented product design is shown in Fig. 1. In this study, the product design process comprises two processes: (1) problem recognition and ideation and (2) evaluation of design solutions. EFSM, MP environments and the SD method are applied to

support product design processes. Although they are useful independently, more effective utilization of local information can be realized by combining them. As local characteristics, function-structure mapping data on a local product, information related to that local product, the physical environment of the living-sphere and satisfiers of human needs are reflected in the FSM, EFSM, MP environment and SD method, respectively.

Before product design goes ahead, an EFSM and MP environment are developed by a design engineer, field observer, field expert and system developer. For development of the EFSM, an FSM of the reference product in the target region is compiled based on reverse engineering (Otto & Wood 1998) by a design engineer. The FSM comprises a method of describing a product and is widely used in functional analysis for clarifying the decomposed function and structure trees of a product and for visualizing the relationship between sub-functions and components (Pahl & Beitz, 1988). Reverse engineering initiates the redesign process in which a product is predicted, observed, disassembled, analyzed, tested, “experienced” and documented in terms of its functionality, form, physical principles, manufacturability and ease of assembly (Wood et al. 2001). Here, a design engineer collects information about not only the FSM but

also data from actual experience.

Then, related local information and a product usage profile are selected and linked to a product sub-function and component of the FSM by a design engineer (Fig. 2). This information link provides evidence for the function or structure of the reference product. The EFSM supports recognition and ideation, focusing on specific regional or local characteristics by visualizing the relationship between critical local information and the related function and/or component (Sugita et al., 2017). In other words, the EFSM is a tool for applying indigenous knowledge to product design based on engineering.

Local information is collected through field observations by a field expert before development of the EFSM and MP environment. In field observations, an observer collects local information, focusing on usage of all products in the living environment, including descriptions in natural language, interviews with locals and photography/video filming. Furthermore, satisfiers, as defined by Max-Neef, are identified in needs-based workshops held in the target area (Kobayashi, et al., 2019). Each satisfier is described in natural language and tends to satisfy fundamental human needs.

In the process of evaluating product design, evaluators experience product use cases in an MP environment, which involves subjective evaluation using the semantic differential (SD) method (Osgood et al., 1957). A living space where the target product is used in daily life is reproduced in the MP environment. This environment comprises tangible prototypes of real products and their virtual models to increase the evaluator’s sense of agency. It allows for visual observation through a head-mounted display and also evaluation of the workload associated with the movement of the evaluator’s body and tactile sensation while using the product.

Based on the local information obtained from field observations, a typical living space in the observed target region is reconstructed in a VR space created to the same scale as that of the real space. In addition, the evaluator’s limbs are reproduced in the VR space, and their movement reflects the movement of the evaluator’s actual hands and feet in the real space. In the real space, simplified physical prototypes that the evaluator can touch are placed in the same positions as those of the products created in the VR space. The virtual models are overlaid on the physical prototypes, and MP enables the evaluator to experience motion, load and a sense of touch that approximate reality.

After completing the experience, the evaluators rate the impression of their experience by assigning scores for pairs of evaluation criteria. The SD method measures the psychological attributions of an individual’s attitude toward something. It focuses on the connotative meaning of objects, events and concepts, and is suitable for measuring emotional and behavioral aspects of an

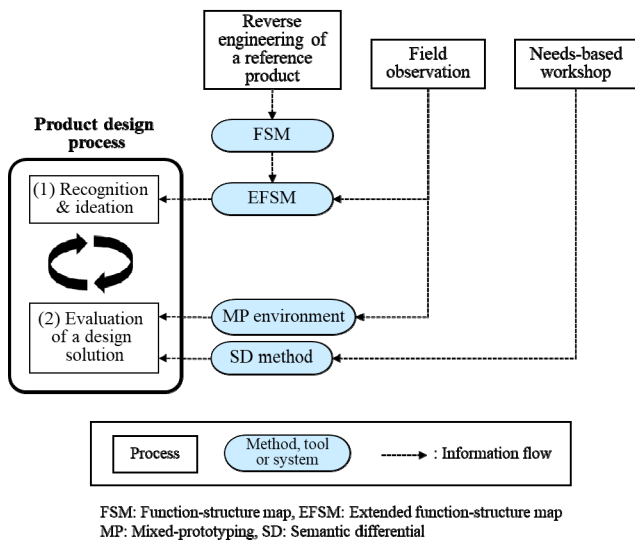


Fig. 1 Proposed framework for locally-oriented product design.

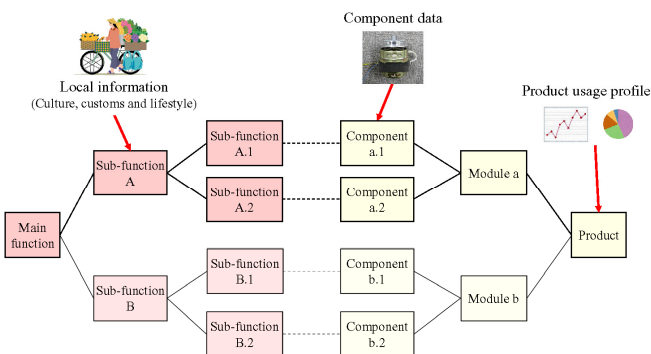


Fig. 2 Schematic of the extended function-structure map. (EFSM).

individual's attitude (Klement et al., 2015). It consists of multiple sets of adjectives with opposite meanings such as "hot ↔ cold" that are divided into 5 or 7 levels and each is set as an evaluation criterion.

In this study, the evaluation criteria used in the SD method were extracted from satisfiers (Max-Neef, 1991) acquired from needs-based workshops in the target region. Requirements for the product are connected to the related satisfiers, and the connected satisfiers are converted into adjectives. Pairs of these bipolar adjectives (i.e., antonym pairs) are used as the evaluation criteria. The evaluation results are analyzed by comparing the score of each criterion for the target product before and after introducing design improvements.

The purpose of the proposed framework is appropriate application of local information with different properties to two product design processes. Namely, we apply 1) descriptive information on product use, lifestyle, climate and culture to create an EFSM, and on satisfiers to evaluate design solutions, and 2) spatial information from photos and videos to establish an MP environment. By using this framework, varied local information can be utilized to design locally-oriented products.

## 4. Example Application

### 4.1 Field Observation

In recent years, environmental issues have been surfacing due to population and economic growth in Southeast Asia (Kishita, et al., 2018). Although the gross domestic product (GDP) per capita in Vietnam is lower than that in high-income countries, its economic growth rate is the highest in Southeast Asia, so it is important to design locally-oriented products for Vietnamese consumers at reasonable prices. In this study, we focus on the washing machine as an example application of the proposed design framework.

Figure 3 shows a bathroom inside a traditional Vietnamese house. It consists of a washing machine and wash basin, a shower and a toilet. This configuration is typical in Vietnam. Here, clothes are washed by hand in the wash basin and/or washing machine. The custom of hand washing is popular because Vietnamese people commonly think that stains cannot be removed by available washing machines alone. Figure 4 shows wash basins for washing clothes and dishes outside the house.

### 4.2 Reverse Engineering

As an example application, we designed a new twin-tub washing machine for lower-middle-class Vietnamese people. In the same target user segment in other South Asian countries, such as Indonesia and the Philippines, twin-tub washing machines are relatively popular. However, in this study, we designed this type of washing machine for the Vietnamese market; we disassembled a single tub washing machine for sale

in a Vietnamese market and used it as the base product. Figure 5 shows the reference product disassembled. This product consists of relatively few parts compared with those sold in high-income countries.

### 4.3 Recognition and Ideation using EFSM

Figure 6 shows a screenshot of the visualization system for the EFSM made by adding a component structure and related local information to the FSM of the base product. The window in the upper-left of the figure contains the following local information: "Residents believe that washing by hand and then putting the clothes in the washing machine is the best way to remove dirt, but because they are busy, they wash their clothes in the washing machine only," "washing machines are fast and convenient, but people believe that hand washing removes



Fig. 3 Bathroom in a traditional Vietnamese house.



Fig. 4 Wash basins for washing clothes and dishes.



Fig. 5 The local reference product disassembled.

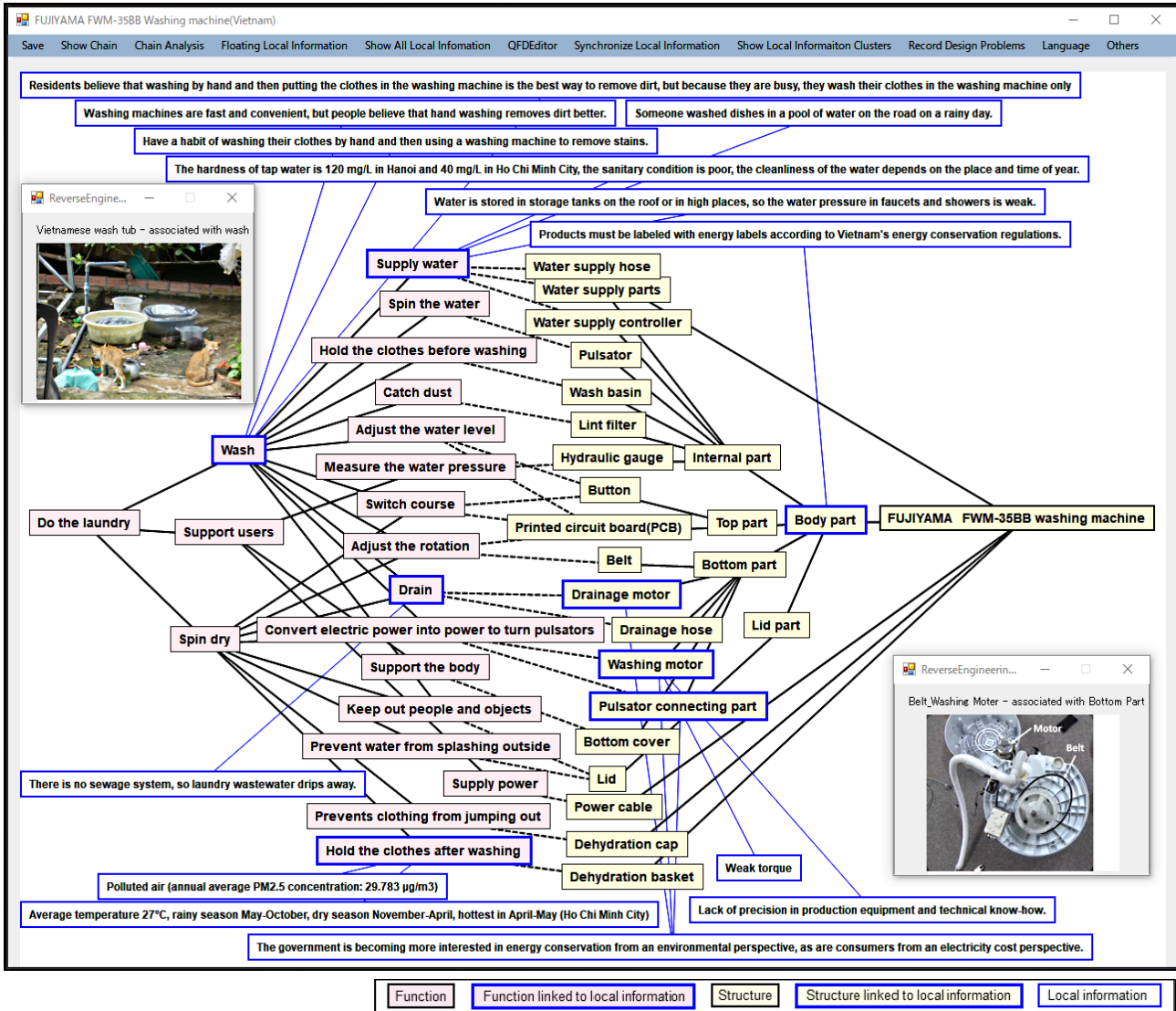


Fig. 6 A screenshot of the visualization system for the EFSM of a Vietnamese washing machine.

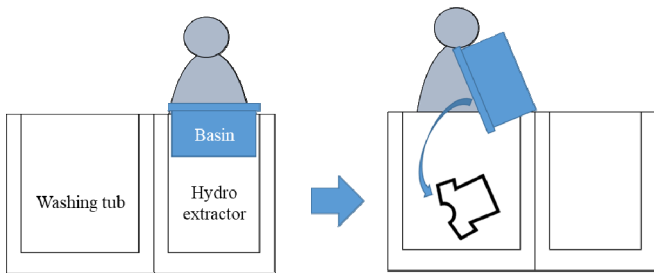


Fig. 7 A schematic of the design concept.

dirt better,” and “Have a habit of washing their clothes by hand and then using a washing machine to remove stains.” Also, the window in the lower-right area of the figure contains the following information: “Weak torque” and a photograph of the washing motor. A design engineer examined all the above information and came up with the idea of combining hand and machine washing in a single product.

From the results, we designed a combination of wash basin and twin-tub washing machine, as shown in Fig. 7. To facilitate the task of daily laundry, our new design solution introduces a wash basin attached to the drum

opening of the hydroextractor, which enables manual washing on top of the machine while standing.

#### 4.4 Design Solution Evaluation in an MP Environment Following the SD Method

We investigated replacing a fully automatic washing machine (reference product) with a locally-designed twin-tub washing machine including a wash basin in an MP duplication of the bathroom of a traditional Vietnamese house.

Before enlisting local people to experiment, we converted satisfiers gathered from workshops (Kobayashi, et al., 2019) held in Vietnam into 13 evaluation criteria based on the SD method as follows: calm ↔ restless, formed ↔ formless, healthy ↔ sick, comfortable ↔ uncomfortable, refreshed ↔ weary, free ↔ bound, cautious ↔ rash, accomplished ↔ awkward, clean ↔ dirty, delicate ↔ rough, satisfied ↔ dissatisfied, easy ↔ painful, and relaxed ↔ strained. In this experiment, the evaluation criteria were rated between 1 and 7, with a higher score indicating a more positive evaluation.

Furthermore, we constructed an MP environment

based on images of a bathroom that we visited during the field observation (Fig. 8). The hands and feet of the evaluators were reproduced in the virtual space, and these virtual models were linked to the evaluators' actual hands and feet in the real space. In addition, we placed simplified prototypes of the washing machine, washtub, water and laundry items in the real space, as shown in Fig. 9.

The two types of washing machines were installed in the MP environment of the same Vietnamese bathroom and were evaluated by three Vietnamese people (two men and one woman). These evaluators were immersed in the virtual bathroom including the physical prototypes and carried out the laundry process using the washing machines. First, they evaluated the fully automatic washing machine when carrying out the preliminary process of manual washing using the wash basin on the floor. Then, the fully automatic washing machine was replaced with the twin-tub washing machine, which involved manual washing in the wash basin attached to the top of the machine while standing.

The average values of the three evaluators for each criterion are shown in Fig. 10. The total average for all the criteria was 4.8 for the fully automatic washing machine and was slightly higher at 5.0 for the twin-tub washing machine. However, the score for “easy” decreased from 6.7 for the fully automatic washing machine to 5.3 for the twin-tub washing machine. Switching between the washing, rinsing and wringing processes and the work of transferring the clothes from the washing tank to the hydroextractor (i.e., the wringing and spinning tank) were found to lower the scores of the evaluation criteria for the twin-tub washing machine, but not necessarily for the fully automatic washing machine. These manual processes also resulted in lower scores for “calm,” “pleasing,” “refreshing” and “relaxed.”

In contrast, the score for “free” increased because the quantity of water and washing time could be easily adjusted with the twin-tub machine. “Delicate” was connected to many requirements for laundry and is the only criterion connected to the requirement of “doesn't damage clothes.” This score increased because the newly designed twin-tub washing machine allows manual clothes washing while standing with increased stability. Because none of the scores fell below 4.0, which is the middle value for each criterion, changes in the laundry processes were not considered to have negatively impacted the selected satisfiers.

Although the overall score slightly improved with use of the twin-tub washing machine, the evaluation results for some of the criteria, which were based on satisfiers, suggest that the design needs to be further improved. In particular, the functions and structure of the twin-tub washing machine need to be changed so that it makes transferring clothes from the washing tank to the wringing and spinning tank easier. A detailed design



Fig. 8 Virtual space of the MP environment.

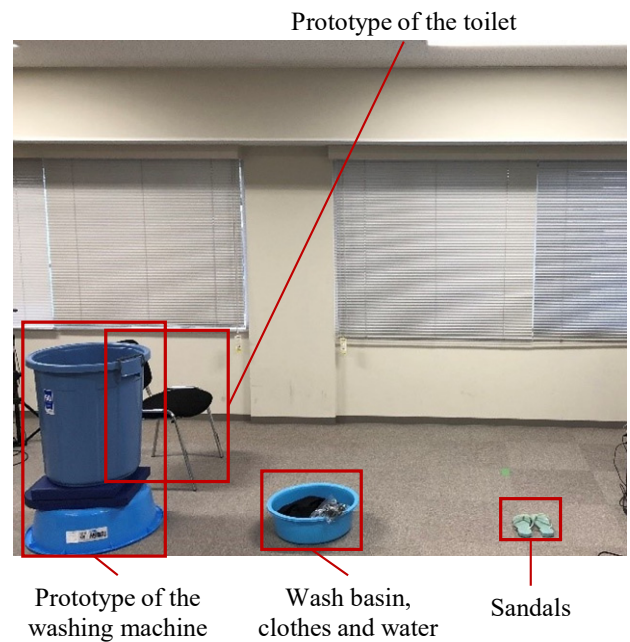


Fig. 9 Tangible prototypes in the MP environment.

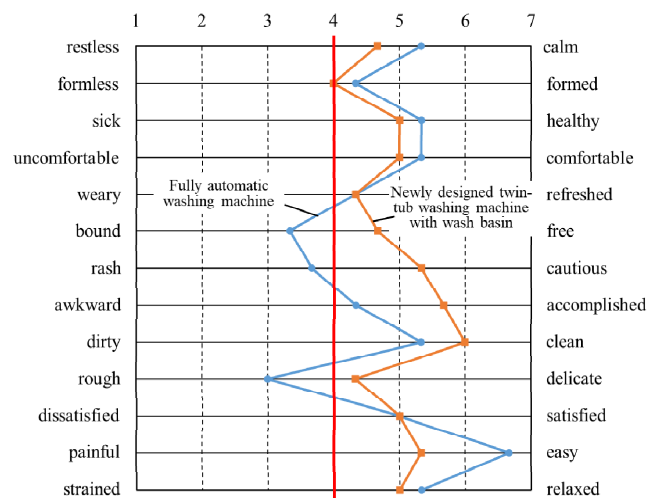


Fig. 10 Average scores of each criterion assigned by three evaluators for two types of washing machines.

review focusing on these features is subsequently required to identify functions that need to be improved.

## 5. Discussion

As described in Chapter 4, the design engineer is required to understand the relationship between local information and the FSM as well as recognize design issues. In this case, the EFSM itself is a concept visualization method in which local information expressed as free-format short sentences is linked to the FSM, which enables the design engineer to recognize design issues and generate design ideas. Thus, local information used in the EFSM should be appropriately arranged for product design. For example, three similar sentences are linked to the function node “Wash” in Fig. 6 because they were observed by different individuals in different field studies. Although we consider that this type of arrangement suggests that the nodes of local information are representative of the general population in the target region and are important, the local information should be analyzed in more detail in future work.

Next, we discuss our evaluation using an MP environment. By reproducing the living space and home equipment in the MP environment, the evaluators could evaluate the products and product use cases holistically within an environment approximating the realities of daily life. However, because differences in the importance of each satisfier and their mutual dependency were not considered in this study, further analysis of the satisfiers is needed. The effect of spatial and temporal discrepancy between virtual objects and tangible prototypes, such as time delays between tactile and visual senses, is another issue that needs to be further analyzed. The limitations of the MP environment in time and space restrict the scope of evaluation to only the in-use process of products within a limited interior space.

In general, the proposed framework can be applied during the early phase of product design. However, life-cycle thinking, including life-cycle planning (LCP), is necessary during the early phase of eco-design (Kobayashi, 2005). Therefore, we will consider a process that integrates the proposed framework and an eco-design framework such as LCP in future work.

## 6. Conclusion

In this study, we proposed a framework for designing locally-oriented products by using an EFSM and MP environment. This framework enables us to utilize different types of local information, namely, descriptive and spatial information for product design, while focusing on local characteristics as appropriate. We demonstrated the usefulness of the proposed framework by applying it to a novel Vietnamese washing machine design. We hope to apply the framework to more design cases using

various types of products in different regions, especially in developing countries in Asia.

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