Abstract
Product platform design and development is an arduous process that involves multiple stakeholders both inside and outside of a company. However, owing to its benefits, product platform has been widely implemented in the industry. Although numerous methodologies for product platform option generation, selection, and optimization have been proposed and demonstrated through various case studies, only a few researchers have explored and demonstrated a product platform design process that considered various value chain impacts. Herein, a value chain and stakeholder-driven product platform design process is introduced. The process is demonstrated through a case study, where different water purifier product platform options were generated and evaluated for their effects on value chain, such as organization structure, production line configuration, economic effect, and preferences of different stakeholders.

KEYWORDS
Product Platform, Quality Function Deployment, Value Chain Analysis, Water Purifier

1 INTRODUCTION
Many modern products are becoming increasingly complex as customers expect more features, better performance, and more customizable options, thereby causing companies to mass customize their products. As custom designing products for all available product market segments is inefficient and cost-prohibitive, many companies have explored different product development strategies to more quickly respond to the needs of customers in different market segments, while being more cost effective. To achieve this objective, one of the most popular product development strategies implemented by various industries is the product platform strategy.

Product platform is a set of common elements shared by a group of product variants, known as the product family. The shared elements include components, interfaces, manufacturing processes and underlying technologies. Using product platform elements as a common base, several product variants with different sets of features can be developed by adding customizable elements. For example, a computer tablet product family consists of several common platform elements, such as operating systems, camera, battery, outside casing and display, central processing unit, component interface, and manufacturing processes. The differentiation for various market segments can be achieved using components with different capacities, such as hard drives, or including features such as cellular service.

Since the case reported by Black and Decker, a product platform strategy has been widely implemented owing to its numerous advantages compared to an individual product development strategy without a product platform. Sharing common platform components results in lower product family unit cost owing to the economy of scale. Sharing common interfaces among products in the product family allows for easy swapping of components of different capacities for product differentiation, and an easy future upgrade provided that the interface is compatible. Sharing common manufacturing processes has benefits, such as flexible product variants production to respond to uncertain demands, and shorter learning periods for production workers when a new product variant is introduced. Sharing common mature technologies imbedded in the product platform allows a product design team to concentrate their efforts on variant-specific technologies only, thus resulting in reduction of development time. All these advantages can result in higher sales and profit margins throughout the product lifecycle. However, a product platform strategy has several drawbacks. The initial development cost for a product platform can be 2-10 times higher than that of a single product, thereby incurring more financial risk. Additionally, product platforms that accommodate both high- and
low-end products can be overdesigned for low-end products, resulting in cost increase.\textsuperscript{7,8} Another fundamental issue is that if the product platform is not sufficiently flexible to accommodate new technologies, it can hamper product innovations, resulting in loss of product competitiveness.

For reasons previously outlined, product platform must be designed to maximize its benefits, while minimizing its drawbacks. This requires a rigorous product platform design process. The process includes identifying customer needs, translating them to engineering requirements and corresponding product elements, and generating viable product platform options. Furthermore, once product platform options are generated, their effect on the overall value chain, such as organization structure, production line structure, economic viability, and stakeholder’s preferences must be assessed to determine the benefits and drawback of the product platform. In this paper, we introduce a value chain and stakeholder-driven product platform design process and demonstrate the feasibility of the process on a water purifier product platform design case study.

\section{LITERATURE REVIEW}

\subsection{Previous works}

A product is an embodiment of a company's response to address particular needs of customers. Product design and development\textsuperscript{6,9,10} is a set of defined activities to plan, conceive, design and launch a new product. Many companies adopt the traditional linear product development process comprising product planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up phases. The software industry adopted a similar process in the form of the waterfall model.\textsuperscript{11} However, with increasing pressure for better product performances and shorter development cycles to remain competitive, product development processes have become more complex and iterative. For many industries, such as defense and aerospace, where their product or system complexities have increased, development processes were adopted to satisfy the requirements. One of the widely used complex system design process is known as the “Vee” process model.\textsuperscript{12} The model divides a design process into a decomposition stage (left side of the V) and integration stage (right side of the V), while incorporating numerous design tools for tracing product or system requirements and managing complexity. For the software industry, more customized development processes, such as spiral development\textsuperscript{13} has been proposed and widely adopted. With the emergence of the Agile development paradigm, other processes, such as Scrum\textsuperscript{14} has been widely implemented.

The aforementioned product development processes are proposed and implemented to design the best product to address the needs of target customers. For a product to be marketable, it needs to satisfy the particular needs of potential customers. Furthermore, to stay ahead of the competition, the product needs to deliver maximum value to both external and internal stakeholders. The product has a good value to external stakeholders such as potential customers if it is well designed to suit their needs. It also delivers good value to internal stakeholders if it can be developed efficiently, while reducing the overall associated costs. To this end, numerous works exploring value-driven design have been published.

For value-driven design to be successfully implemented, customer needs have to be prioritized and mapped to appropriate system requirements and elements. Some of more popular methods to identify customer needs include conjoint analysis\textsuperscript{15} and focus group sessions. Conjoint analysis is based on the statistical analysis of population surveys to determine the needs of potential customers, while focus group sessions identify the needs through a series of focused interviews and is thus qualitative in nature. The identified needs are then prioritized using decision making methods, such as the analytic hierarchy process (AHP),\textsuperscript{16} technique for order preference by similarity to ideal solutions (TOPSIS),\textsuperscript{17} and Pugh method.\textsuperscript{18} Once customer needs are identified and prioritized, they are mapped to system requirements and elements using a variety of available methodologies. Quality function deployment (QFD)\textsuperscript{19} is widely used to map identified customer needs to system requirements and elements using the house of quality. Other mapping methods used are the technical requirements definition process\textsuperscript{20} and object process methodology.\textsuperscript{21}

For actual value-driven design-related research, Collopy and Hollingsworth\textsuperscript{22} provided a comprehensive history, methods, and tools used for value-driven design. Isaksson et al\textsuperscript{23} introduced a value-driven design methodology based on an information-driven approach and demonstrated the methodology using an industrial aircraft development case study. Bertoni et al\textsuperscript{24} suggested an approach for implementing a value-driven design to product service systems, and later proposed a value-driven concept selection method known as early value oriented design exploration with knowledge maturity (EVOKE).\textsuperscript{25} Topcu and Mesmer\textsuperscript{26} developed an end-user value-based demand model to be used in value-driven design to maximize value of the system designed. In recent works, a value-driven design approach has been incorporated into product family design.\textsuperscript{27,28}

Product platform strategy can be viewed as a value-driven design strategy for internal stakeholders. By sharing common elements among different product variants, the product platform can reduce costs and simplify manufacturing processes and supply chains, thus increasing the value of the product family for several stakeholders. However, product platform is a complex system that requires rigorous development processes. Additionally, due to the product platform being the common architecture for several product variants launched in different market segments, the identification and optimization of product platform elements becomes extremely important. Hence, numerous product platform identification and optimization methodologies have been introduced since the formal introduction of the product platform concept in academia.\textsuperscript{2}

Product platform identification methodologies focus on achieving the maximum commonality for platform elements by identifying common elements that belong to the product platform and unique elements that belong to individual product variants for differentiation. Early works focused on establishing suitable design methodologies for product platform design. Simpson et al\textsuperscript{29} introduced a product
platform concept exploration method that can identify competitive concepts for scalable product platforms. Martin and Ishii\textsuperscript{30} proposed a methodology to identify and generate modular product platforms through the use of the generational variety index. Suh et al\textsuperscript{31} proposed a methodology to identify and design a flexible modular product platform that is easy to change when expected future demand and performance criteria changes. Yearsley et al\textsuperscript{32} proposed a Pareto filtering based methodology to identify product platforms and family members. Park et al\textsuperscript{33} used QFD to identify constant and variant engineering requirements for a product platform. Kim and Moon\textsuperscript{34} introduced a methodology for identifying sustainable product platform using a multiattribute decision making approach. Recent advances in this area include work by Schuh et al,\textsuperscript{35} who proposed a product platform identification methodology that utilizes the system module’s degree of freedom, Song et al\textsuperscript{36} who introduced a data-driven approach to product platform identification, and Jung and Simpson,\textsuperscript{37} who proposed an additive manufacturing based product platform and family redesign. Zhang et al\textsuperscript{38} proposed an improved QFD method that incorporated sensitivity analysis to determine product platform parameters.

Parallel to product platform identification-related research, several researchers have focused on product platform and family optimization problem. Gonzalez-Zugasti et al\textsuperscript{39} proposed a product platform optimization approach and demonstrated it on interplanetary spacecraft family design. Nelson et al\textsuperscript{40} transformed a product platform optimization problem into a multicriteria optimization problem with Pareto optimal solutions. Luo et al\textsuperscript{41} introduced a scalable product platform optimization framework based on QFD. Baylis et al\textsuperscript{42} introduced a Pareto optimization framework for optimizing product platform commonality and modularity simultaneously. Numerous studies utilize heuristic algorithms to solve multiobjective product platform and product family design problems to overcome the discrete nature of the product platform design space.\textsuperscript{43–46} Some recent publications extended product platform design and optimization framework to incorporate supply chain, as the platform itself and product variants inevitably affect supply chain operation and costs.\textsuperscript{47–49} Other recent advances in product platform-related research include establishing a relationship between the product platform and inherent system attributes, such as complexity\textsuperscript{50} and changeability,\textsuperscript{51–53} which can be used to optimize product platforms for additional system attributes in addition to commonality and modularity.

2.2 | Research gap and proposed research contribution

A literature survey revealed many valuable research publications in the areas of product development process, customer needs identification methods, customer needs to system element mapping methods, value-driven design, product platform identification, and product platform optimization. After carefully categorizing and analyzing the contents of published literature, it was evident that a majority of product platform-related works were proposing new tools and ideas to improve a particular step of the platform design process. Furthermore, previous works that explored product platform identification and optimization processes started with predefined engineering requirements to map and identify key product platform parameters and elements. The previous studies works rarely extended their processes to include an actual voice of customer (VOC) analysis and value chain stakeholder assessments. Companies implementing product platforms for their products are extremely interested in how to trace their product platform requirements from VOC to actual platform elements, and how their choice of product platforms affects their value chain stakeholders due to organizational structure change, production line architecture change, economic viability, and internal stakeholder’s preferences. These are all business critical objectives seriously considered by decision makers when they make final decisions on the implementation of a product platform.

The product platform design process proposed in this study addresses the aforementioned research gaps in the following ways. The newly proposed process extends the product platform design process to include the VOC analysis and assessment of the value chain. Additionally, the process is demonstrated through a real life industrial case study, in which each step of the proposed process is clearly presented for easy understanding. The case study can serve as a reference example for system engineering practitioners to adopt into their current design process. The results from this study provide useful guidelines for architecting product platforms for researchers and practitioners. In the next section, the proposed design process is presented in detail.

3 | PROPOSED PRODUCT PLATFORM DESIGN PROCESS

3.1 | Design process overview

The product platform design process is similar to the traditional product development process in many aspects. However, as previously mentioned, the commonality of the product family must be considered in designing a product platform. Figure 1 shows the high-level view of the proposed product platform design process.

The process is divided into five steps. It starts with the identification of products that are candidates for inclusion in the same product family and thus can share a common product platform. Once target products for the platform are identified, key customer needs and their priorities are identified in the second step, the VOC analysis. Results obtained from the second step are used as inputs for the third step, in which, through QFD analysis, the identified customer needs are mapped to engineering requirements and then to actual product components. Once the customer needs to engineering requirements to product components relationship is established, various product platform options can be generated in the fourth step. The generated options are then assessed for the various impacts they have on the value chain, before the final product platform option is selected. These individual steps are explained in more detail in subsequent sections.
3.2  Detailed design steps

3.2.1  Step 1: Target products selection

The first step in the process is to select a set of candidate products to be part of the product platform-based family. In the beginning, companies usually offer a single product variant for a specific market segment. However, as time progresses, companies seek to expand their market coverage by offering product variants with different specifications in other market segments to gain more market share and revenue. This results in a proliferation of unique components and manufacturing processes for different product variants, increasing product development, manufacturing, and components costs. At this point, firms begin their assessment for implementing a product platform strategy. Ideally, a product platform can be planned, defined, and designed when companies develop their first product variants. However, this may not be practical when the particular product market is in its infancy. During this period, several product architectures are competing for market dominance, making it risky for companies to invest in product platforms based on a specific architecture. Firms may wait for a dominant product architecture to emerge and then assess their overall product portfolio at that point in time to determine sets of products suitable for aggregation into a common product platform. Through an examination of the overall corporate product portfolio, number of products in the portfolio, sales volume for each product, and similarities between products offered, the firm makes an initial assessment and decision regarding the set of products that can be produced in a common product platform. At the end of this step, selected target products, their specifications, and their positioned market segment information are passed onto the next step as inputs.

3.2.2  Step 2: Voice of customer analysis

For a product to be successful in its market segment, it needs to incorporate key customer needs into product functionalities. To do this, key customer needs for selected products from the previous step must be identified and prioritized for their respective market segments. Typically, customer needs are identified and prioritized through different analysis methods. Widely used methods for VOC analysis are the conjoint analysis,\textsuperscript{15} analytic hierarchy process (AHP),\textsuperscript{16} and focus group sessions. A conjoint analysis consists of surveying a wide group of customers who are either users or potential buyers for the target product using a set of designed questions to identify key needs that the product must address. The AHP determines the weight of each customer need through pairwise comparisons, establishing a quantitative priority for customer needs. For focus group sessions, a small number of people from different groups are interviewed in-depth to identify key customer needs. All these analysis methods are well-proven.

Regarding the product platform design in this step, it is noteworthy that the VOC results can be used to determine the inclusion or exclusion of a specific function in the product platform. If the VOC results indicate that there is consistent demand for a particular customer need across the covered market segment, an effort should be made to assess the inclusion of the identified customer need-related functions in the product platform. However, if the results indicate that a specific customer need is required for a few market segments but not others, the need-related functionalities should be categorized as variant specific functions that can be incorporated into a product that covers the market segment with such a need, differentiating the product from the other product variants based on the same platform. The output of this step is a set of prioritized customer needs, used as inputs to the QFD analysis, as described in the next step.

3.2.3  Step 3: Quality function deployment

As the prioritized customer needs have been identified in the previous step, the next step is to establish the logical relationship between the identified customer needs, engineering requirements, and product components. One of the more popular engineering design tools to accomplish this mapping process is QFD. Through the series of layered HOQ, customer needs are mapped to respective product engineering requirements and then to product components. The strengths of the relationships between customer needs, engineering requirements, and product components are determined by subject matter experts, and are expressed in the HOQ, using a range of scores. The end result for this step is a set of layered HOQ matrices, which is a traceable map from the customer needs identified in Step 2 to product engineering requirements, and then to actual product components.

3.2.4  Step 4: Product platform option generation

A product platform, by definition, is a set of common elements shared by product variants in the same product family. These are essential
elements for performing functions common to all product variants. In this step, different product platform options are generated using the analysis results from the previous process steps. The generated configurations differ by the inclusion or exclusion of specific elements related to specific functions. One platform option may not include a specific function-related element in order to use it for product differentiation. Another platform option may include that specific function in order to assess the impact of the value chain for including or excluding the function from the product platform, which is a form of sensitivity analysis. The output from this step is a set of product platform options that are assessed for their value chain impacts in the subsequent step.

3.2.5 Step 5: Value chain impact assessment

As the final step of the proposed process, the generated product platform options are assessed for their impact on the value chain. The choice of the product platform has a significant effect on the value chain, such as organization structure, production line configuration, economic effect, and stakeholder preferences. Hence, they need to be selected after careful evaluations considering several different criteria.

4 CASE STUDY: WATER PURIFIER PRODUCT PLATFORM DESIGN

4.1 Case study overview

Woongjin Coway Co., Ltd. is a major Korean water purifier manufacturing company. They offer several water purifier products across different market segments. With increasing competitions from other companies entering the water purifier market, the firm is under pressure to reduce the overall development cost and render their development processes more efficient to retain their market share and profitability. Currently, their products are designed and developed product-by-product basis. Some localized efforts have been made to reuse and share key components across different products. However, it is clear that more systematic strategy to design and develop their future product portfolio is required. Responding to the current challenge, the company is considering product platform strategy implementation for their future water purifier product portfolio. Figure 2 shows the current water purifier market segments and the company’s products, positioned in their respective market segment.

The water purifier market is divided into residential and commercial segments. Purifiers manufactured for the residential segment are countertop purifiers intended for home use, while those manufactured

FIGURE 2 Water purifier market segments and proposed products for platforming
TABLE 1 Internal expert’s opinion on water purifier market and product platform strategy

| Expert’s role     | Opinions on water purifier market trend and product platform strategy                                                                 |
|-------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| Research fellow   | • Water purifier market is still growing, but slowly  
                    • Need a product portfolio diversification strategy  
                    • Need a good strategy to respond to varying customer needs |
| Chief engineer    | • Entry of new competitions resulting in product price decrease, thus changing market dynamics  
                    • Need to explore new markets with high growth potential  
                    • Need for purifier performance and technology improvement  
                    • Water purifier architecture has reached maturity, ready for product platform strategy implementation |
| Project manager 1 | • Speed of new trend for water purifier market has decelerated as the market matured  
                    • Expect development time and production time reduction and quality improvement when the product platform strategy is implemented |
| Project manager 2 | • Simultaneous product planning for domestic and global markets  
                    • Owing to absence of long term product strategy, many products are developed without regard to reuse and commonality  
                    • Current organization structure is unsuitable for platform-based product development |
| System design engineer | • With advanced market maturity, price, rather than system performance, is the deciding factor for purchase decision  
                        • Implementation of product platform strategy can yield reliability and quality improvement owing to common system integration and development |

for the commercial segment are stand-alone purifiers intended for public use. Each segment is divided further into smaller sub segments based on purifier filter type and additional incorporated functions. The vertical axis is the water purifier price. From the current product portfolio, four countertop water purifiers are chosen as target products to be included in the product platform. The chosen products are independently developed products that currently do not share a common platform. However, they are in close proximity to each other in the market segment, providing a good opportunity for grouping them into a platform-based family. The chosen water purifiers share several common functions: water purification, water storage, cold water supply, and hot water supply, all of which are addressed through the product platform design process and incorporated in the final product platform.

4.2 VOC analysis

The next step is to identify and prioritize the VOC for water purifiers. Prioritized customer opinions obtained by VOC analysis are essential for designing product platform and products for the target market segment. However, other internal designs and technological and product trend issues must be considered. To gather data for customer opinion and internal opinion, two different surveys were conducted. The target interviewees for the first survey were company’s internal subject matter experts, who were closely involved in the water purifier development. The second survey targeted potential customers. The internal stakeholder survey was conducted in a one-to-one interview format, yielding qualitative results. The second survey, targeting potential customers, was conducted in a conjoint manner, yielding quantitative results.

4.2.1 Internal VOC

For capturing the internal VOC, five experts, each with more than ten years of experience, were interviewed. The experts consist of a research fellow, a chief design engineer, two project managers, and a system design engineer. They provided opinions on the current water purifier market trend and the need for a product platform strategy. Table 1 summarizes the opinions collected from five internal experts.

The internal experts universally stated that the water purifier market has reached maturity, with its dominant product architecture decided and competition market reaching the saturation point. They have further stated that the time is right for implementing the product platform strategy, to gain more profitability through commonality in product-related elements, such as components, production line, and organization structure.

4.2.2 External VOC

The second survey, targeted to potential customers, was conducted from April 16 through May 9, 2017, in which total of 1000 participants with purchase decision authority were interviewed in person. The interviewees were presented with 25 key customer needs (CNs) that affect water purifier purchase decision. The customer needs range from basic function-related needs to safety- and additional feature-related needs. The interviewees were asked to rate each CN using a 1 - 5 scale, 1 being the least important and 5 being the most important for purchasing a product. The accumulated results produce the average CN score (CS) for m CNs. Once the CS for each CN is obtained, it is converted to a normalized CN importance weight (CW). Table 2 shows
TABLE 2  Surveyed CN, CS, and CW values for water purifier

| CNi | CNi description | CSi (1 ~ 5) | CWi (%) |
|-----|----------------|------------|---------|
| 1   | Reliable purification performance | 4.8        | 5.21    |
| 2   | High energy efficiency           | 4.5        | 4.88    |
| 3   | Bacteria free                   | 4.3        | 4.66    |
| 4   | Sanitary water dispensing section | 4.2        | 4.56    |
| 5   | Less noise                      | 4.2        | 4.56    |
| 6   | Continuous supply of cold water  | 4.1        | 4.45    |
| 7   | Convenient filter exchange       | 4.1        | 4.45    |
| 8   | Pretty design                   | 4.1        | 4.45    |
| 9   | Water must be sufficiently cold  | 4.0        | 4.34    |
| 10  | Water must be sufficiently hot   | 3.9        | 4.23    |
| 11  | Easy operability                | 3.9        | 4.23    |
| 12  | Continuous supply of hot water   | 3.8        | 4.12    |
| 13  | Zero fire risk                  | 3.8        | 4.12    |
| 14  | Good water taste                | 3.7        | 4.01    |
| 15  | Automatic sterilization         | 3.7        | 4.01    |
| 16  | Water temperature control       | 3.7        | 4.01    |
| 17  | Easy installation               | 3.7        | 4.01    |
| 18  | No additional water drops after dispensing | 3.5 | 3.80 |
| 19  | Quick water cooling             | 3.5        | 3.80    |
| 20  | Quick water heating             | 3.4        | 3.69    |
| 21  | Slim size                       | 3.3        | 3.58    |
| 22  | Water dispensing amount control | 2.7        | 2.93    |
| 23  | Water dispensing space simplification | 2.6 | 2.82 |
| 24  | Water overflow or leak prevention | 2.4 | 2.60 |
| 25  | Automatic lighting adjustment   | 2.3        | 2.49    |

The 25 key CNs for water purifier, with their corresponding CS and CW, sorted by CW values.

\[
CW_i(\%) = \frac{CS_i}{\sum_{i=1}^{n} CS_i} \times 100\%.
\]  

The survey results indicated that potential buyers expect water purifiers to perform their core and common functions reliably. Based on the list, several high-ranked CNs were related to the common water purifier function defined previously. They include the following: reliable purification performance (CN1), continuous supply of cold water (CN6), water must be sufficiently cold (CN9), water must be sufficiently hot (CN10), and continuous supply of hot water (CN12). The water storage function is not included, as it is a basic function that is essential to the product. Other CNs were defined based on needs that can enhance product performance, but were not considered essential.

4.3 | Quality function deployment

The next step is QFD analysis that maps CNs to appropriate engineering requirements, and subsequently to product components. Key water purifier engineering requirements (ER) are discussed and agreed by the internal experts who provided inputs for the internal survey. A conceptual first-level HOQ is shown in Figure 3.

In the HOQ, each CN is mapped to the related ER using entries in the CN-ER relationship matrix R1. The entries in each cell of the R1 matrix are assigned as follows. If the ith CN is affected by the jth ER, a score of 9 (high), 3 (medium), 1 (low), or 0 (no effect) is assigned, depending on the effect strength. Using the R1 matrix, weight for each of n engineering requirements, EWj, can be calculated as

\[
EW_j(\%) = \frac{\sum_{i=1}^{n} CW_i R1_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{n} CW_i R1_{ij}} \times 100\%.
\]  (2)

where \( R1_{ij} \) is the relationship score for the ith CN on the jth ER in the R1 matrix. The metric measures the total effect of a specific ER within a set of total engineering requirements, given their effect on the CN.

For water purifier, 25 major ERs were selected by the internal experts. Figure 4 shows the first HOQ, with the EW values for each ER at the bottom. It is noteworthy that the CNs are sorted by the order of CW values from top to bottom, and the ERs are sorted by the order of EW values, from left to right.

Next, the identified ERs are mapped to water purifier components in the second-level HOQ. ERs and EWs from the first HOQ were placed in rows and major purifier product components (PC) were placed in columns. The input for the related ER-PC relationship matrix R2 were filled similarly to the first-level HOQ matrix R1, using the same scoring scale. The product component importance weight (PW) for the kth component can be calculated using Eq. (2).

\[
PW_k(\%) = \frac{\sum_{j=1}^{n} EW_j R2_{kj}}{\sum_{j=1}^{n} \sum_{k=1}^{n} EW_j R2_{kj}} \times 100\%.
\]  (3)
Figure 5 shows the second-level HOQ for the water purifier that maps ERs to key PCs. Similar to the first-level HOQ, ERs and water purifier PCs are sorted in the order of their respective EW and PW values. Through VOC and QFD analyses, important CNs, ERs, and CPs were identified and prioritized. Table 3 shows the identified CNs, ERs, and CPs for the water purifier, in the order of their importance weight.

4.4 Product platform option generation

The next step is to generate product platform options. Product platform, by definition, must include elements that are required for performing product family’s common functions. First, from the list of CNs, VOCs related to common water purifier functions were identified. Next, the ERs and CPs that strongly affect the given CNs ($R_{1ij}$ and $R_{2ij}$ value is 9) were identified. Finally, the identified CPs were grouped into distinct modules for possible inclusion in the product platform.

As mentioned in the VOC analysis step, the selected water purifiers share four common functions. Carefully inspecting CNs, six CNs related to the common functions were identified. Tracing the CNs to ERs, five key ERs were identified. Finally, 11 CPs that affect the key ERs significantly were selected for inclusion in the product platform. A small number of water purifier components not related directly to the common purifier functions were included owing to the design and supplier constraints. Table 4 lists the CNs, ERs, and CPs related to the product platform.

With candidate product platform components identified, the next task is to group the selected components into the appropriate modules. This was performed primarily to improve the efficiency of the assembly
process. After discussion with subject matter experts, the components were grouped into two modules, as shown in Figure 6.

The primary module consists of components that perform water purification and cooling/heating. The tank module consists of components that perform water storage and cooling/heating functions. With the proposed product platform modules, different product platform options were generated as described below.

4.4.1 Baseline option

The baseline option represents the current product development practice, where each of four water purifiers are developed individually, without sharing any common product platform. This option serves as a reference point for comparing other product platform options.

4.4.2 Platform option 1

The first product platform option proposed was to use the primary module only. For this option, the tank module is customized for each product, having different water storage capacities, which is one of the key differentiating factors for the water purifier.

4.4.3 Platform option 2

The second option proposed was to include both the primary and tank modules in the product platform. If these two modules are included in the platform as common modules, the water purifier family can benefit from additional commonality. However, due to making the water storage capacity common, a key differentiating feature is lost.

It should be noted that the comparative value chain analysis of two options can also be interpreted as a sensitivity analysis by which the value chain impact of including or excluding a specific feature or engineering requirement can be assessed. The water storage capacity, which is one of the common water purifier functions listed in Table 4, is not included in the first platform option. The second platform option included this as one of the common functions which is a part of the water purifier platform. The results of the value chain assessment in
TABLE 3  Key CNs, ERs, and CPs for water purifier in the order of their importance weight values

| No. | Customer needs (CN)                                      | Engineering requirements (ER)                     | Water purifier components (CP)         |
|-----|-------------------------------------------------------|--------------------------------------------------|---------------------------------------|
| 1   | Reliable purification performance                     | Water cooling time                                | Compressor                            |
| 2   | High energy efficiency                                | UX usability satisfaction                         | Condenser                             |
| 3   | Bacteria free                                        | Water heating time                                | Main tank                             |
| 4   | Sanitary water dispensing section                     | Overheat shutoff                                  | Main frame                            |
| 5   | Less noise                                           | Ice forming prevention                            | Hot water tank                        |
| 6   | Continuous supply of cold water                      | Hot water temperature                             | Euro switching feed valve             |
| 7   | Convenient filter exchange                           | Water extraction control                          | Cooling coil                          |
| 8   | Pretty design                                        | Electricity consumption                           | Cold water temperature sensor         |
| 9   | Water must be sufficiently cold                       | Euro conversion                                   | Front deco PBA                        |
| 10  | Water must be sufficiently hot                        | Cold water temperature                            | Filter support cover                  |
| 11  | Easy operability                                     | Noise level                                       | Membrane filter                       |
| 12  | Continuous supply of hot water                       | Sterilization                                     | Outer part                            |
| 13  | Zero fire risk                                       | Overflow sensing                                  | Main filter                           |
| 14  | Good water taste                                     | UX visibility satisfaction                         | Base cover                            |
| 15  | Automatic sterilization                              | Bacteria removal rate                              | Overflow sensor                       |
| 16  | Water temperature control                            | Customized hot water system                       | CDS sensor                            |
| 17  | Easy installation                                    | Energy saving mode                                | Full tank sensor                      |
| 18  | No additional water drops after dispensing           | Faucet sterilization                              | Connector hose (hot water tank)       |
| 19  | Quick water cooling                                  | Automatic dispensing                              | Tray/grill                            |
| 20  | Quick water heating                                  | Water taste                                       | Separator                             |
| 21  | Slim size                                            | Filtration performance                            | Sterilization fitting                 |
| 22  | Water dispensing amount control                      | Illuminance sensor based LED shutoff              | Installation adapter                  |
| 23  | Water dispensing space simplification                | Dispensing amount selection                       | Sterilization module                  |
| 24  | Water overflow or leak prevention                    | Full water-level sensor                           | Drain pump                            |
| 25  | Automatic lighting adjustment                        | Empty water-level sensor                          | Faucet                                |

TABLE 4  CNs, ERs, and CRs related to the water purifier product platform (from Table 3)

| Common water purification functions | Common function-related CN                                      |
|-------------------------------------|-----------------------------------------------------------------|
| 1. Water purification               | 1. Reliable purification performance                            |
| 2. Water storage                    | 6. Continuous supply of cold water                             |
| 3. Cold water supply                | 9. Water must be sufficiently cold                              |
| 4. Hot water supply                 | 10. Water must be sufficiently hot                               |
|                                    | 12. Continuous supply of hot water                             |

| Common function-related ER          | Common function-related CP                                      |
|-------------------------------------|-----------------------------------------------------------------|
| 1. Water cooling time               | 1. Compressor                                                   |
| 3. Water heating time               | 2. Condenser                                                    |
| 6. Hot water temperature            | 3. Main tank                                                    |
| 10. Cold water temperature          | 5. Hot water tank                                               |
| 15. Bacteria removal rate           | 6. Euro switching feed valve                                    |
|                                    | 7. Cooling coil                                                 |
|                                    | 8. Cold water temperature sensor                                |
|                                    | 10. Filter support cover                                        |
|                                    | 11. Membrane Filter                                             |
|                                    | 13. Main filter                                                 |
|                                    | 14. Base cover                                                  |

4.5  Value chain impact assessment

The selection of product platform option affects the product development value chain variously. Quantitative and qualitative assessments for generated options were conducted. Several stakeholders were interviewed, and they provided helpful feedbacks regarding how each product platform option would affect their respective processes and deliverables.

4.5.1  Organization structure

To better implement the product platform strategy, internal experts recognized the need for changing the product development organization structure. Figure 7 shows the current product development organization structure and the proposed product platform-based organization structure.

The current organization structure consists of the product planning team and individual product design teams. The product planning team is responsible for planning, procurement, production, and quality control. They provide product planning that is subsequently assigned to individual product design teams. However, collaborations among different product design teams to use common design elements have not been realized. In the newly proposed organization structure, the subsequent section highlights the qualitative and quantitative sensitivities of adding or removing this particular feature from the product platform.
new platform design team is added, whose responsibilities include common platform system design and project management, providing common design basis and guideline for individual product development. Individual product design teams design their assigned product, following general guidelines established by the platform design team on the use of common platform elements. The organization structure established for product platform implementation can reduce redundant R&D efforts and ensure the maximized benefit of platform-based commonality. With the implementation of new organization structure, experts believe that the product platform strategy can be implemented more efficiently.

4.5.2 Production line structure

Currently, each water purifier is manufactured on a dedicated production line that can be vulnerable to fluctuating individual purifier demand. With product platform strategy implementation, the production line can be redesigned such that the water purifiers in the product family share several common assembly sequences. Figure 8 shows the production line configurations for all three product development options.

The production line shown for the baseline option is a single product line, with each water purifier manufactured in its dedicated line. The production line consists of a supplier segment, subassembly segment, and the main assembly segment. For the first platform option, the product family shares three assembly sequences, highlighted in the figure. The production line for the second platform option is similar to that of the first platform option, except the common main tank subassembly sequence, owing to the sharing of the common water tank module.

Once the detailed assembly sequences were identified, additional analysis was conducted to estimate the productivity of each option. It was calculated that for the two platform options proposed, the assembly time was reduced by an average of 9% in comparison to the current baseline option assembly time. The analysis results indicate significant labor cost saving, as the total annual manufacturing units for all products in the product family is close to 200,000 units. It is noteworthy that no significant assembly time differences appears between platform options 1 and 2.

4.5.3 Economic analysis

A key reason for implementing the product platform strategy is cost reduction through using common platform elements. In addition to the previously mentioned labor cost saving, using common product platform components can reduce the initial tooling investment cost. For economic analysis, the initial tooling investment costs for all water purifiers in the product family for three proposed options were calculated. Table 5 lists the number of new molds required for each water purifier in the product family, with the normalized tooling investment cost shown in parentheses.

A comparison of the initial tooling investment costs reveal that significant savings can be achieved through product platform strategy implementation. The cost savings for platform option 1 was 13.6%, while that for platform option 2 was 21.8%. Additionally, Table 6 shows the investment cost payback period for individual water purifiers for all development options, with differences in payback period expressed in percentages, in parentheses.

The payback period was different for each product owing to the initial investment cost and number of purifiers manufactured per month. As expected, two platform-based options were economically
FIGURE 8 Assembly line setup for three options (common assembly sequences highlighted)

TABLE 5 Number of new molds required for water purifier development under different product development options

| Water purifier products | Baseline | Platform option 1 | Platform option 2 |
|-------------------------|----------|-------------------|-------------------|
| Product 1               |          |                   |                   |
| Product 2               |          |                   |                   |
| Product 3               |          |                   |                   |
| Product 4               |          |                   |                   |
| Total                   |          |                   |                   |

TABLE 6 Payback period for water purifier investment under different product development options

| Water purifier products | Baseline | Platform option 1 | Platform option 2 |
|-------------------------|----------|-------------------|-------------------|
| Product 1               |          |                   |                   |
| Product 2               |          |                   |                   |
| Product 3               |          |                   |                   |
| Product 4               |          |                   |                   |

advantageous compared to the current baseline option. Comparing the two platform-based options, the second option with a common tank module demonstrated faster payback period, as expected.

4.5.4 Stakeholder preferences

Many stakeholders participated in various stages of the product development process. Each stakeholder’s preference on the product platform option is different, depending on the stakeholder’s roles and responsibilities. Table 7 lists the value chain stakeholders involved, with their preferred choice in product platform option and the justifications for their choices.

Although the majority of stakeholders preferred the second platform option, some stakeholders whose deliverables are directly affected by sales volume preferred the first platform option. At the time of writing this manuscript, the projected sales volumes under different product development options were not available. Once these numbers are available, decision makers can make informed choices on which platform options to implement.

4.6 Case summary

In this section, a detailed case study to generate and assess water purifier product platform options is presented. The case study started with the collection and prioritization of customer VOCs. QFD was performed to map the VOCs to major water purifier engineering requirements, subsequently mapped to the appropriate components. Several components related to the purifier’s common functions were selected as candidates for product platform components, and were grouped into the primary module and tank module. Different product platform options were generated, and their effect on value chain were assessed, including organization, production, economic viability, and stakeholder preferences.

The results of the case study revealed that for the product platform options, the second option indicated clear advantage owing to the benefits from commonality. However, some stakeholders have
expressed preference for the first platform option, where the platform consists of the primary module while differentiating the tank module. This was owing to the concern for decreasing sales volume and revenue from the lack of water storage capacity differentiation, which is a key product specification. Decision makers who are responsible for establishing the platform option selection must evaluate and balance the analysis results and value chain stakeholder’s preferences before making the final decision.

5 | CONCLUSION AND FUTURE WORK

In this study, a new value chain stakeholder-driven product platform design process was proposed. The process started with the identification and prioritization of customer needs. Subsequently, the customer needs were mapped to key engineering requirements and product components through QFD. Product platform elements were identified through the QFD results and opinions of subject matter experts. Once the product platform elements and different options were defined, various analyses were conducted to assess the effect of the product platform on the overall value chain. The proposed process was demonstrated through a detailed case study, where a product platform for a set of water purifiers was defined using the process. Two different product platform options were generated, and various analyses were conducted to compare the company-wide effect for each platform option.

The proposed product platform design process contributes to existing product platform literature by introducing a traceable design process from customer needs to product platform elements and to value chain stakeholder assessments. An additional contribution is made through the industrial product family case study, providing a detailed step-by-step demonstration of the new process. We believe this will serve as a helpful reference for researchers and practitioners who aim to adopt the proposed process. A key future scope that can be explored is a systematic sensitivity analysis for the inclusion and exclusion of a specific function in the product platform, as part of the common functions shared by all variants of the product family. Through this sensitivity analysis, system architects can assess the advantages and disadvantages of the product platform, with and without a specific function. Another promising future scope is expanding the value chain analysis to include other assessments such as revenue and profit analysis, which can be of significant interest to system architects as well as final decision makers. Finally, the work presented in this paper can be used to balance the degree of commonality, variety, and profitability to satisfy various stakeholders in the entire value chain. These are only a few examples of the possible future research topics that can be pursued to improve the front-end product platform architecture generation and selection process.

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