Product platforms design, selection and customisation in high-variety manufacturing

Published Version:
Galizia, F.G., ElMaraghy, H., Bortolini, M., Mora, C. (2020). Product platforms design, selection and customisation in high-variety manufacturing. INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH, 58(3), 893-911 [10.1080/00207543.2019.1602745].

Availability:
This version is available at: https://hdl.handle.net/11585/688881 since: 2020-01-20

Published:
DOI: http://doi.org/10.1080/00207543.2019.1602745

(Article begins on next page)

Product platforms design, selection and customization in high-variety manufacturing

Francesco Gabriele Galizia[a], Hoda ElMaraghy[b,*], Marco Bortolini[c], Cristina Mora[c]

[a]University of Padova, Department of Management and Engineering
Stradella San Nicola 3, 36100 Vicenza, Italy

[b]Intelligent Manufacturing Systems Centre, University of Windsor
401 Sunset Avenue, Windsor N9B 3P4, Ontario (Canada)

[c]University of Bologna, Department of Industrial Engineering
Viale del Risorgimento 2, 40136 Bologna, Italy

* Corresponding author: Hoda ElMaraghy
E-mail: hae@uwindsor.ca

Abstract

Product platforms represent an effective strategy implemented by manufacturers to cope with dynamic market demands, decrease lead-time and delay products differentiation. A decision support system (DSS) for product platforms design and selection in high-variety manufacturing is presented. It applies median-joining phylogenetic networks (MJPN) for the platforms design and phylogenetic tree decomposition for platforms selection by determining the product family phylogenetic network and defines the platforms at various levels of assembly corresponding to different trade-offs between number of platforms (variety) and number of assembly/disassembly tasks (customization effort). Product platforms are reconfigured and customized to derive final product variants. The phylogenetic tree is decomposed in multiple levels, from the native platforms to the final variants. New Platforms Reconfiguration Index (PRI) and Platforms Customization Index (PCI) were developed as metrics to evaluate the platforms customization effort. A case study of a large family of plastic valves is used to demonstrate the DSS application. It shows reduction of 60% in platforms variety and increase in platform customization assembly/disassembly tasks by only 20% leading to significant production and inventory efficiencies and cost savings. This methodology supports companies in the design and selection of best product platforms for high-variety to reduce cost and delivery time.

Keywords: mass customization; delayed product differentiation; product platform customization; median-joining phylogenetic networks; product variety management

1. Introduction

In modern industry, manufacturers face with a high level of product innovation, market globalization, dynamic customer demand and technological advancements (Shou et al. (2017), Bortolini, Galizia, and Mora (2018)). These trends encourage industrial companies to adopt the mass customization paradigm to meet every customers' request and satisfy their individual needs (Gilmore 1997). The main advantage of such strategy is to provide different goods to customers with the same quality and prices of the mass-produced products (Su et al 2010). In this scenario, companies are switching from Make-To-Stock (MTS) and Make-To-Order (MTO) strategies to Delay Product Differentiation (DPD) in order to implement mass customization. DPD is a hybrid strategy that strives to reconcile the dual needs of high-variety and quick response time, by utilizing the concept of product platforms (Gupta and Benjaafar 2004). A product platform is defined as a set of sub-systems and interfaces that form a common structure from which a stream of derivative product variants can be efficiently produced and developed (Meyer and Lehnerd (1997); Simpson, Siddique and Jiao (2006)). In particular, a common product platform is manufactured to stock (MTS) in the first stage of production which is then differentiated into different products after demand is known in the second stage, i.e. manufactured to order (MTO) (Gupta and Benjaafar 2004). A large number of industrial companies introduced product platforms as tool to reach the benefits of DPD. Sony, for the development of the Walkman (Sanderson and Uzumeri 1995), Kodak, Black & Decker (Simpson, Siddique and Jiao 2006) and Hewlett-Packard (Meyer 1997) are among the most relevant applications.

This paper proposes an integrated decision support system (DSS) for product platforms design and selection in high-variety manufacturing to best manage the trade-off between platforms variety and number of assembly/disassembly tasks and customize the platforms selected to produce the final product variants. The Median-Joining Phylogenetic Networks (MJPN) supports the design phase by identifying the different product platforms, their number and composition, and the use of both assembly and disassembly to customize them into product variants. MJPN methodology is traditionally used in biology to predict the living species' ancestry by linking them to their descendants, through gaining and losing of genes (Bandelt, Forster, and Röhl (1999), Hanafy and ElMaraghy (2015)), but its use in the assembly and manufacturing field is relatively new. To the Authors' knowledge, the unique contribution of its use in this field is found in Hanafy and ElMaraghy (2015). The methodology builds the so-called phylogenetic network tree, which shows the transformation of each platform into a variant through gaining and losing of components and, unlike most models found in literature, it does not require in advance the specification of the number of platforms to develop. The developed DSS proposes two new metrics to evaluate the effort to reconfigure the platform into a variant by considering the required number of assembly and disassembly tasks, i.e. Platforms Reconfiguration Index (PRI), and the ease of assembly and disassembly factors, i.e. Platforms Customization Index (PCI), at each level of the phylogenetic tree. Such indices provide conditions that support industrial companies in determining, for each product variant, whether it is better to adopt DPD or assemble to order (ATO) strategy, and guide them in the selection of effective product platforms. To illustrate and validate the steps of the proposed DSS, it is applied to a large real case study involving manufacturing 1553 items, representative of a Small & Medium Enterprise (SME).

The remainder of this paper is organised as follows: section 2 reviews the relevant literature. Section 3 presents the original DSS for product platforms design and selection, while section 4 presents the DSS application to a real industrial case study. Finally, section 5 concludes the paper with final key outcomes and conclusions.

2. Literature review

This section is organized into two parts. The former explores the DPD concept and the methods and techniques used for product platforms design, and the latter introduces metrics and indices developed to model the assembly and disassembly tasks, which represent the two operations to perform in order to customize a platform into a variant.

2.1 Delayed product differentiation and product platform concept

The ability of a manufacturing system to have high product variety and short lead times offers a competitive advantage. Industrial companies that strive to reach this ability prefer to produce a limited portfolio of products (Gupta and Benjaafar 2004). In this context, items can be produced to stock (MTS) to minimize lead times, but such a solution becomes costly when the number of final products is large and it is also risky in presence of dynamic market demand and short product life cycles. Manufacture to order (MTO) is another key production strategy where production does not start until a customer order is received. Applying this strategy, inventory can be reduced but customer lead times increase (Rajagopalan (2002), Rafiei and Rabbani (2012), Olhager and Prajogo (2012)). Delayed Product Differentiation (DPD) is a hybrid strategy that postpones the final product assembly differentiation point as much as possible (He, Kusiak, and Tseng 1998). Postponement can be divided into form postponement and time postponement (Zinn and Bowersox (1988), Yang, Burns, and Backhouse (2004)). Blecker and Abdelkafi (2006) state that form postponement describes all the activities initiated after the arrival of customer orders. Hsu and Wang (2004) propose a dynamic programming model for the tactical planning using an AND/OR graph to determine the product differentiation points. The impact of deferment on capital investment and inventory risk-pooling effects are quantified and incorporated in the model. Swaminathan and Tayur (1998) introduce a model to find the best configuration and inventory level of product platforms and compare the performance of such production strategy with that of MTO and Assemble-To-Order (ATO) processes providing managerial insights into the conditions under which one may be better than the other. He and Babayan (2002) state that the successful implementation of DPD strategy lies in efficient scheduling of the manufacturing system. In their study, they define and solve the scheduling problems in implementing a DPD strategy in a general flexible manufacturing systems consisting of machining and assembly stations. Ko and Jack Hu (2008) propose a binary integer programming model for task-machine assignment and workload balancing in complex asymmetric configurations, since such configurations have often been used for delayed product differentiation. AlGeddawy and ElMaraghy (2010a) introduce an innovative design methodology to derive and represent an assembly line layout for delayed products differentiation by using cladistics classification. The resulting cladogram identifies the points of DPD and resembles the physical assembly system layout and was demonstrated for a family of electric kettle variants. AlGeddawy and ElMaraghy (2010b) extend this cladistics model by adding product assembly line balancing constraints to the classification algorithm. Hanafy and ElMaraghy (2015) develop a methodology for assembly line layout for DPD using phylogenetic networks. The proposed model is used to design product platforms and determine the assembly line layout of modular product families.

The Delayed Product Differentiation strategy aims to reconcile the dual needs of high-variety and quick response time by introducing the concept of product platforms (Gupta and Benjaafar 2004). Product platform is defined as a set of sub-systems and interfaces that form a common structure from which a stream of derivative products can be efficiently produced and developed (Meyer and Lehnerd 1997). Khajavirad, Michalek, and Simpson (2009) define a multi-objective genetic algorithm to design product families and product platforms of universal electric motors. The objective function maximizes product efficiency and commonality among modules along with decreasing motors' weight. Jose and Tollenaere (2005) propose an in-depth literature review of the product platform concept focusing on the efficient product family development. They found that it is necessary to best balance the introduction of new techniques to increase components commonality and increasing products distinctiveness. Williams et al. (2007) introduce the Product Platform Constructal Theory Method (PPCTM) as a technique enabling the designers to develop platforms for customizable products and apply this method to determine a platform map of a cantilever beam. Yu, Yassine and Goldberg (2007) use the Design Structure Matrix (DSM) combined with GA to design common platforms for complex products. Moon et al. (2008) develop a multi-agent model to configure product platforms considering the functional model. However, the model cannot handle large product families. Ben-Arieh, Easton and Choubey (2009) propose a mathematical model to configure single and multiple platforms by adding and/or removing components to/from the platforms to get the final variants. However, the model requires the specification of the expected number of platforms a priori. Furthermore, the proposed model is not scalable and requires a formulation based on the application of a genetic algorithm (GA) to solve problems having a large number of products and components. While the most common product platform concept is based on adding or assembling components to the platform to produce product variants, the recent literature proposes the idea of both assembling and disassembling components to/from platforms to customize them and get the final variants (Ben-Arieh, Easton, and Choubey (2009), Mesa et al. (2014), Hanafi and ElMaraghy (2015), Mesa et al. (2015), Mesa, Esparragoza, and Maury (2017)). This emerging strategy based on both assembly and disassembly operations leads to an increase in the number of components in a platform, which means more delay in product differentiation and, consequently, the mass production of a larger product portion, i.e. the platform. The assembly/disassembly of components to/from a platform to obtain product variants is very similar to the concept of evolution, i.e. acquiring and losing characteristics in biological organisms. Phylogenetic networks are used to trace this kind of evolution and predict the living species' ancestry by linking them to their descendants, through gaining and losing of genes. Although the research in DPD is rich, some research gaps remain. In particular, the use of both assembly and disassembly to arrive at the final product variant, which can increase the number of components shared across a product family, is rarely used. This strategy is called "Customized Platforms To Order (CPTO)" (Aljorephani 2017).

2.2 Effort in assembly/disassembly tasks

An important topic in the study of product platforms design using both assembly and disassembly is the effort involved in reconfiguring and customizing the platforms to get the final variants. The effort associated with the reconfiguration can be modeled in different ways, considering for example the number of assembly/disassembly tasks to be performed to change it from a platform to a product variant, and/or assessing the difficulty to assemble and/or disassemble components to/from the platform. Focusing on the assembly tasks, Samy and ElMaraghy (2010) propose a product model to assess assembly complexity of individual parts taking into account the principles of Design for Assembly (DFA). They demonstrate how the model would lead to a reduction of product assembly complexity and the associated cost. Miller et al. (2012) explore the automation of the estimated assembly time by reducing the level of design details required. In particular, they define a complexity metric through artificial neural networks to measure such assembly time. A similar study is proposed by Owensby and Summers (2013). They present an automated tool for estimating assembly times of products based on a complexity metric model. Orfi, Terpenny and Sahin-Sariisik (2011) introduce five main dimensions of product complexity identifying different complexity sources in product design, development, manufacturing and assembly. Their overall goal is to define a unified product complexity metric to be used as a tool to improve product design and manage product complexity. Rodriguez-Toro et al. (2003) review the concept of complexity to support assembly-oriented design and to guide the designers in manufacturing a product with an effective balance of manufacturing and assembly difficulty. Thevenot and Simpson (2006) tackle the product family design problem and propose relevant commonality indices to assess the amount of commonality within a product family, e.g. the developed Percent Commonality Index from the assembly viewpoint measures the percentage of common assembly sequences among products. Concerning disassembly, Lee and Ishii (1997) and Kroll and Carver (1999) propose complexity metrics associated with the final disposal phase of the products. Boothroyd and Alting (1992) and Bryan et al. (2007) highlight the importance of integrating parts when possible to reduce the assembly and disassembly tasks during the early design stages. However, research assessing the effort associated with both assembly/disassembly tasks are rare. Mesa, Esparragoza, and Maury (2017) propose a metric to assess the complexity of assembly/disassembly tasks in open architecture products.

Starting from this scenario, the proposed DSS provides two new metrics integrated with the product platform design that evaluate the effort to reconfigure the platforms into variants at each level of the phylogenetic tree, i.e. the Platforms Reconfiguration Index (PRI) and the Platform Customization Index (PCI). The former considers the assembly and disassembly tasks involved into platform reconfiguration while the latter considers the ease of assembly and disassembly factors, in addition to their number, since they affect the time it takes to accomplish these tasks. Next Section 3 describes the proposed DSS.

3. A decision support system for product platforms design and selection

In this paper, a decision support system (DSS) is proposed to guide industrial companies and practitioners in the design and selection of efficient product platforms, managing the trade-off between platforms variety and required platforms customization effort represented by the time and difficulty of assembly and disassembly tasks. Product platforms are designed by applying the Median Joining Phylogenetic Networks (MJPN). This methodology is traditionally used in biology and its use in the manufacturing and assembly field is relatively new. In particular, it is used in the design phase to define the number and composition of different platforms using both assembly and disassembly to customize the platforms into product variants as needed. In the proposed DSS, it is assumed that components can be disassembled without damage (e.g. fastening), hence, preserving product quality integrity during platforms reconfiguration.

3.1 Methodology

The phylogenetic networks concept has continued to evolve over time, due to the huge number of derivatives obtained from the first concept of unity of species' origins by Darwin (Hanafy and ElMaraghy 2015). Such networks can be classified in two categories: rooted and unrooted networks (Huson and Scornavacca 2011). The cladistics classification methodology is the main branch of rooted phylogenetic networks and major literature contributions on the use of such approach in manufacturing and assembly field are found in AlGeddawy and ElMaraghy (2010a) and AlGeddawy and ElMaraghy (2010b). The MJPN algorithm belongs to the unrooted phylogenetic networks. It has been used in biology to trace and classify DNA sequences according to their relationship to hypothetical ancestral nodes, called median vectors (Bandelt, Forster, and Röhl 1999). Such algorithm builds a network tree (Figure 1) that relates DNA sequences, which in this case are the product variants (from P1 to P10), to each other by the definition of median vectors, which represent the product platforms (from PL1 to PL3) through the majority consensus concept. *Network 5.0* software (Fluxus-engineering.com 2012) is used to build the phylogenetic network. This software is able to compute two main types of algorithms: the median-joining to build a full joined network of species and its inferred ancestry, and the reduced-median to perform the same analysis but only in case of difficulties in interpreting the full median-joining network.

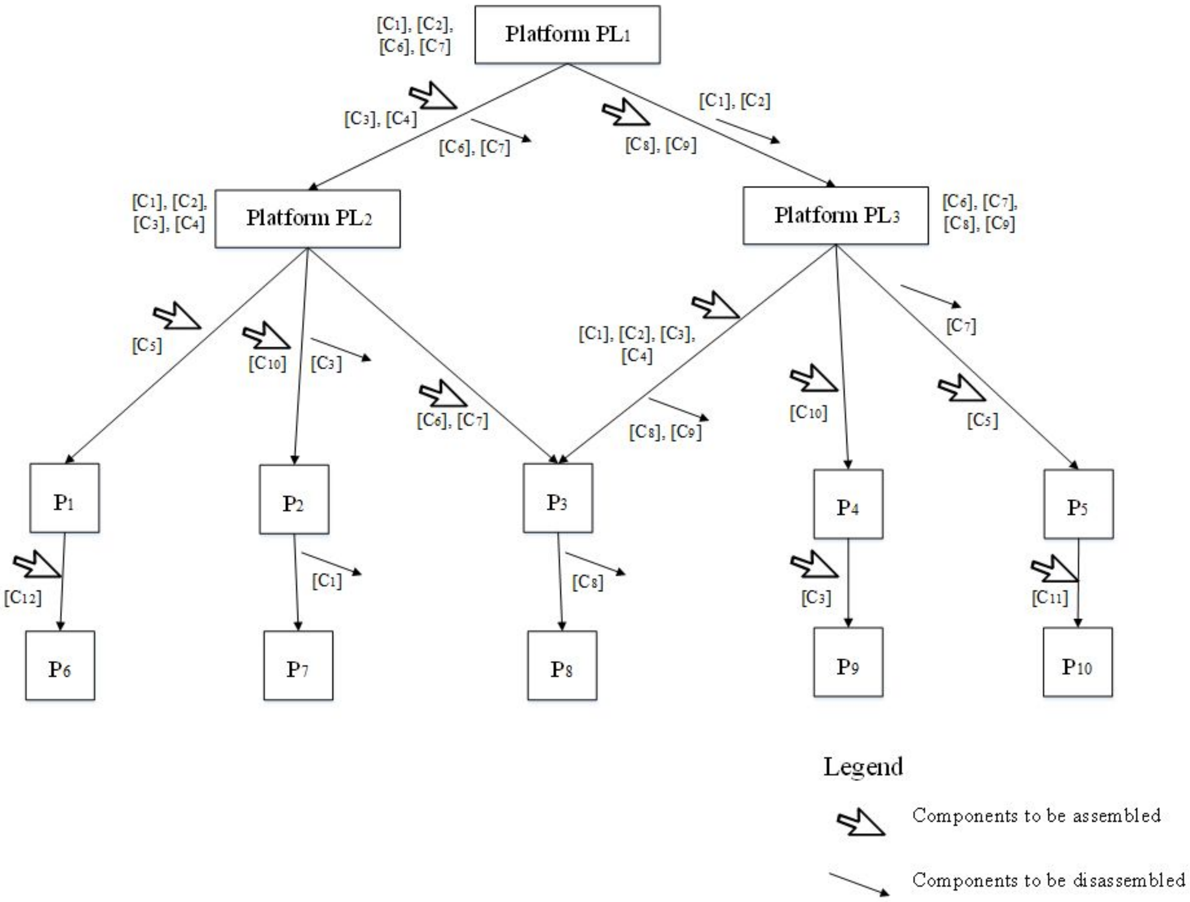

Figure 1. Example of phylogenetic network tree for a product family and its variants and components

In the example shown in Figure 1, the product family is composed of ten product variants (indicated from P_1 to P_{10}) and of a total number of twelve components (indicated from C_1 to C_{12}). The MJPN algorithm creates three product platforms (indicated from PL_1 to PL_3) for this family.

3.1 The proposed DSS

Figure 2 shows a general schematic of the proposed methodology, which has four main steps:

- Step I: Product family definition
- Step II: Product platforms design and definition of assembly/disassembly relationships
- Step III: Platforms variety and Platforms customization effort analysis
- Step IV: Selection of best product platforms

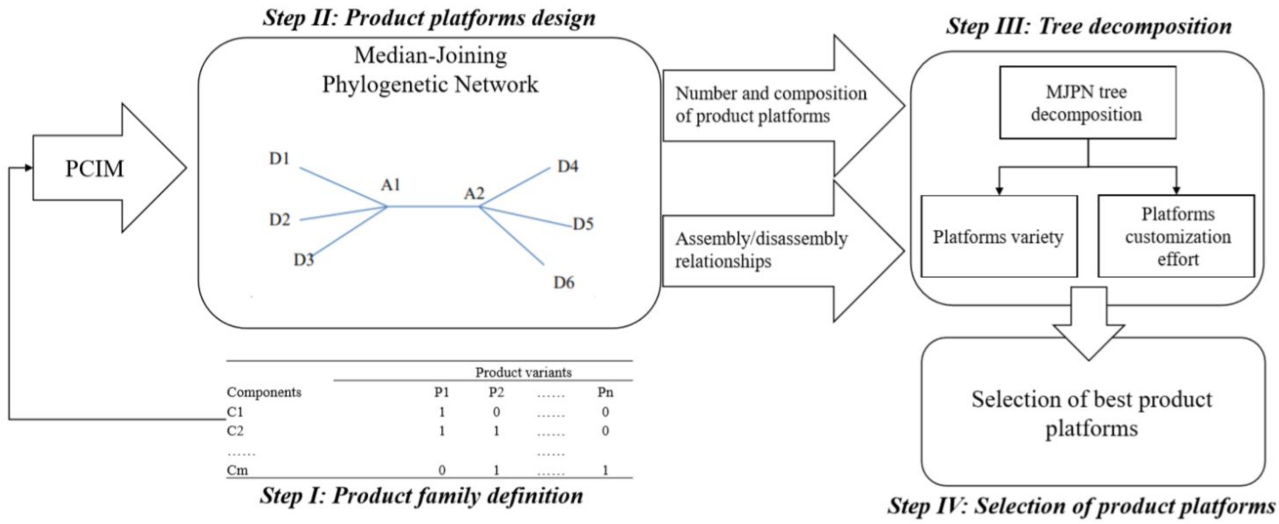

Figure 2. Schematic of the proposed decision support system (DSS)

3.1.1 Product family definition

The methodology starts with the selection of a product family for which the introduction of product platforms is required. The input of this step is the generic bill of materials (BOM) for each product belonging to the family while the output is the definition of the PCIM. Considering n product variants from 1 to P_n and m components in the product variant from 1 to C_m, the PCIM includes X_{mn} binary elements such that:

$$X_{mn} = \begin{cases} 1, & \text{if Cm is in Pn} \\ 0, & \text{otherwise} \end{cases}$$

3.1.2 Product platforms design and definition of assembly/disassembly relationships

In this step, the Median-Joining Phylogenetic Networks (MJPN) algorithm is applied to design the product platforms for the considered product family. As shown in Figure 2, the algorithm input is the PCIM. It builds the phylogenetic network tree, containing the number and the composition of the generated product platforms as well as the assembly/disassembly relationships. Such relationships are crucial to visualize the specific platforms involved in each product reconfiguration and specify which component to add or remove to customize the platform to a product variant or to change from a product variant to a new variant configuration (Mesa, Esparragoza, and Maury 2017).

3.1.3 Platforms variety and platforms customization effort analysis

The third step of the proposed decision support system (DSS) manages the phylogenetic tree decomposition supporting the product platforms selection process. Product platforms have to be designed and selected to maximize the number of components in each platform in order to reduce the number of assembly/disassembly tasks to be performed to obtain the desired product variant while minimizing the number of different platforms to be assembled and stored in order to reduce variety, inventory costs and storage space. Step III addresses this trade-off: the phylogenetic tree obtained in the second step (Figure 1) is decomposed into multiple levels

(Figure 3) from the native platforms (Level 1) to the final variants (Level L). A native platform is a platform that has no incoming arrows (PL1 in the reference example), while a platform or a product variant belongs to level L if it does not have outgoing arrows (from P6 to P10 in the referenced example).

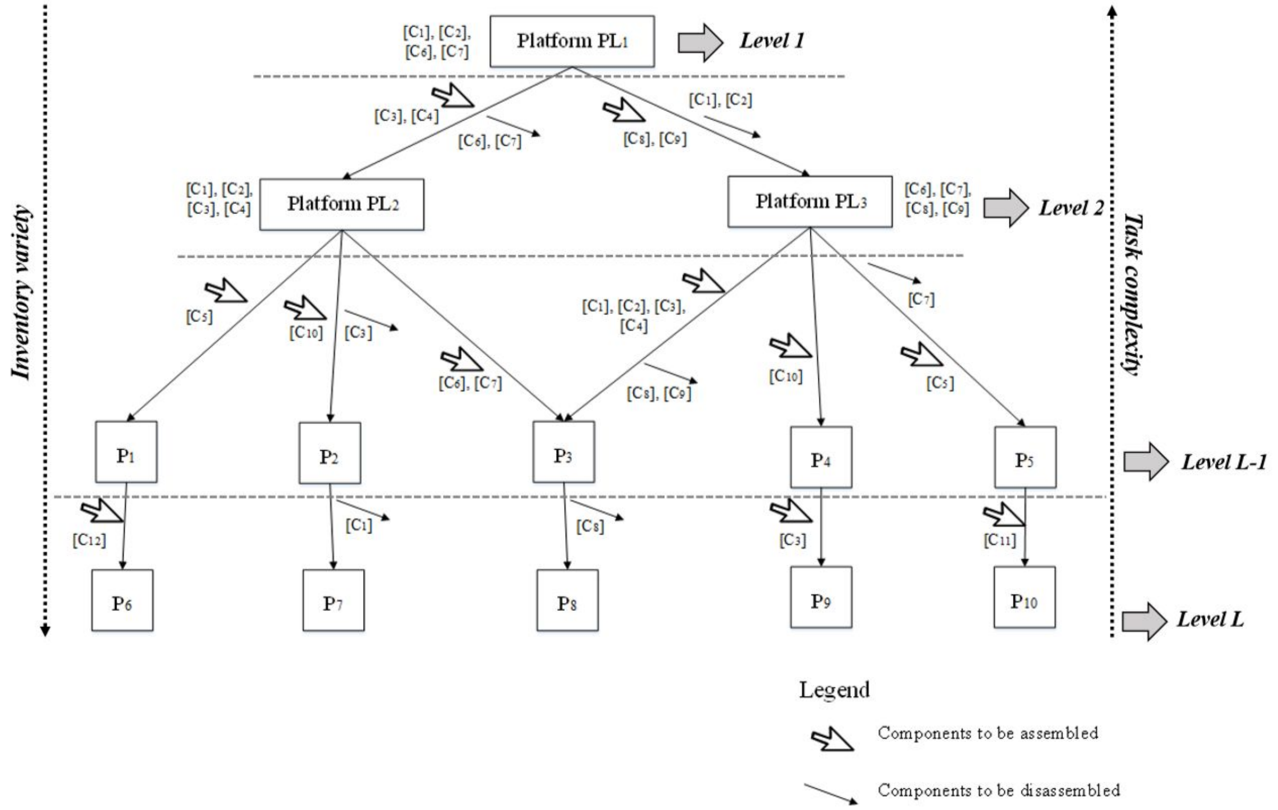

Figure 3. MJPN tree decomposition for platforms selection

Each level corresponds to a different trade-off between the number of types of platforms to be stored, i.e. *platforms variety*, and the number of assembly/disassembly tasks to convert platforms to variants, i.e. *platforms customization effort*. In particular, as platforms number/variety increases from Level 1 to Level L, the platforms customization effort decreases. The platforms selection procedure is characterized by the following steps:

1. MJPN tree decomposition into levels (l = 1...L);
2. For all levels (from 1 to L-1), determine platforms variety and platforms customization effort. Platforms variety represents the number of types of platforms formed in the considered level. The platforms customization effort is assessed by determining the proposed Platforms Reconfiguration Index (PRI) and Platforms Customization Index (PCI). These indices model the effort needed to reconfigure each platform into a variant thus they are indicative of the cost of platform reconfiguration.

Platforms Reconfiguration Index (PRI)

The Platforms Reconfiguration Index (PRI) is an index capable of capturing the effort to reconfigure the product platform into a specific variant by considering the number required of assembly and disassembly tasks. The mathematical formulation of PRI follows:

Indices

v	variants v = 1,…,V
p	product platform p = 1,…,P

Parameters

NCA_{pv}	number of components to assemble to platform p to get variant v
NCD_{pv}	number of components to disassemble from platform p to get variant v
NCV_v	number of components per variant v
PRI_{vp}	Platform Reconfiguration Index (to get variant v from platform p)
PRI	Global Platforms Reconfiguration Index for all platforms

The mathematical formulation of the PRI index to customize a specific platform into a variant is expressed by Equation 1:

$$PRI_{vp} = \frac{NCA_{pv} + NCD_{pv}}{NCV_v} \qquad \forall\, v = 1,\dots,V \qquad (1)$$

The condition $NCA_{pv} + NCD_{pv} < NCV_v$ determines, for each specific product variant, whether it is better to adopt delayed product differentiation (DPD) or assemble to order (ATO) strategy. Specifically, if the condition is true, DPD strategy would be suitable for implementation in the case company, otherwise ATO would be preferable. Therefore, to determine the threshold values of PRI_{vp}, the following three cases are considered:

- Total overlap between product platform and product variant: in this case $NCA_{pv} = NCD_{pv} = 0$ and $PRI_{vp} = 0$ and no effort is required for platform reconfiguration;
- No overlap between product platform and product variant: in this case the condition $NCA_{pv} + NCD_{pv} > NCV_v$ is true. This implies that the ATO strategy is to be implemented. Considering NCA_{pv} and NCD_{pv} as the number of components involved in the assembly/disassembly tasks, $NCD_{pv} = 0$ and $NCA_{pv} = NCV_v$. Hence, $PRI_{vp} = 1$. In this case, the required platform reconfiguration effort is maximum;
- Partial overlap between product platform and product variant: the variant and the product platform share some components, and may require some assembly and/or disassembly tasks to be performed, in which case $PRI_{vp} = \frac{NCA_{pv} + NCD_{pv}}{NCV_v}$.

To summarize $0 \leq PRI_{vp} \leq 1$. PRI_{vp} indices can be further computed over the variants to get an average PRI index for each level of the phylogenetic tree, as expressed in Equation 2:

$$PRI = \frac{\sum_{v=1}^{V} PRI_{vp}}{V} \qquad (2)$$

Platforms Customization Index (PCI)

A Platforms Customization Index (PCI) is proposed by considering the ease of assembly and disassembly factors, in addition to their number, since they affect the time it takes to accomplish these tasks. The time needed to customize the product platform by performing additional assembly tasks can be represented by the value of their respective two-digits assembly codes introduced by Boothroyd, Dewhurst, and Knight (2011). The value of these digits is representative of the ease/difficulty and of the time needed for manual/automatic handling and insertion of each component during assembly operations. For example, assume for a given part that the manual or robotic handling code is 31 and assembly by insertion code is 26, then the assembly effort for this one task would be (3+1) + (2+6) = 12. Each code digit has a value in the 0-9 range, therefore, 36 represents the maximum value (maximum difficulty) of manual/automatic handling and insertion for each component. The time needed for disassembly tasks is estimated by applying the Unfastening Effort Model (U-Effort model) and the corresponding Unfastening Effort Index (UFI) introduced by Sodhi, Sonnenberg, and Das (2004). For each fastener type used for disassembly, the U-Effort model identifies several causal attributes and uses these to derive the UFI score for a given disassembly case. The UFI scale is defined in the 0-100 range, where 100 represents the most difficult disassembly case. It is appropriate to use the U-Effort model since the majority of non-destructive disassembly operations - a pre-requisite for use of the platform assembly/disassembly approach - involve unfastening. The mathematical formulation of PCI is as follows:

Indices

c	components $c = 1,\dots,C$
v	variants $v = 1,\dots,V$
p	product platform $p = 1,\dots,P$

Parameters

ACI_{cpv}	assembly customization index (handling and insertion two-digit codes for assembly of component c to platform p to get variant v)
DCI_{cpv}	disassembly customization index (U-effort index for disassembly of component c from platform p to get variant v)
PCI	Platforms Customization Index for all platforms

$$PCI = \frac{\sum_{v=1}^{V}[(\sum_{c=1}^{C} ACI_{cpv}) + (\sum_{c=1}^{C} DCI_{cpv})]}{\max(ACI_{cpv}, DCI_{cpv})} \quad (3)$$

PRI and PCI values are calculated for all levels $l = 1,...,L-1$ of the phylogenetic network tree. Level L is not considered in the analysis since the selection and subsequent storage of items, i.e. product variants, belonging to this level corresponds to the initial case of MTS strategy. The outputs of this step, for each level, are the values of platforms variety and platforms customization effort.

3.1.4 Selection of best product platforms

In this step, the decision maker is able to select a proper product platforms configuration, which best balances such a trade-off using the values of platforms reconfiguration and platforms customization effort indices for each level of the phylogenetic network tree. This decision is not universal but is specific to the industrial company and products under consideration. After the selection phase, the company manufactures and stocks the platforms following the MTS strategy. Platforms are modular entities composed of the components most shared within the product family and can be reconfigured into different variants by assembly and disassembly of components when a customer order is received. As stated in section 3, it is assumed that components can be disassembled from the platforms without damage through manual assembly operations while products including permanent joining operations, e.g. welding, would not be suitable. This condition prevents damages and ensures high integrity and quality during platforms reconfigurations.

4. Industrial case study

A real industrial case study is considered to illustrate and validate the steps of the proposed decision support system (DSS). The case company manufactures pipe fittings and valves in different plastic materials using injection molding machines and each product model is available in different sizes, colours and materials for a total of 1553 items, which represents very high product variety. Production volume and demand trend are shown in Figure 4 and Figure 5.

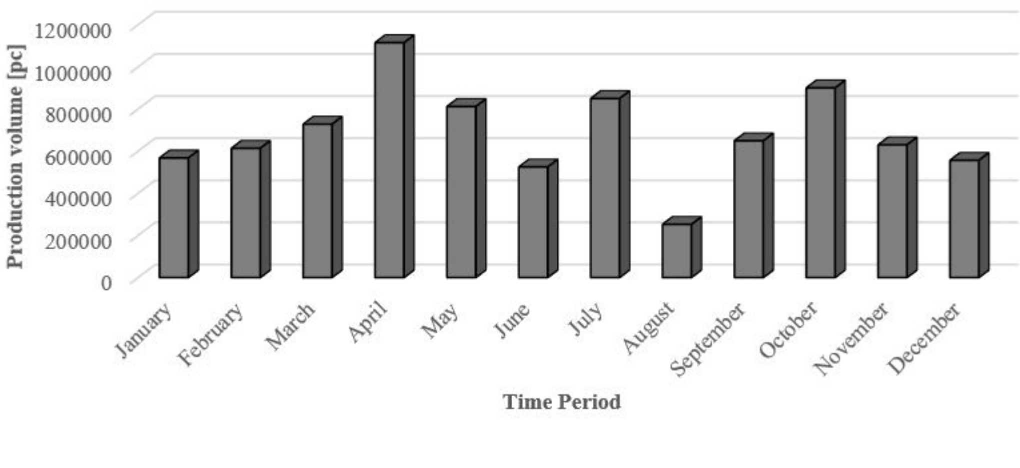

Figure 4. Annual production volume variation for the case company

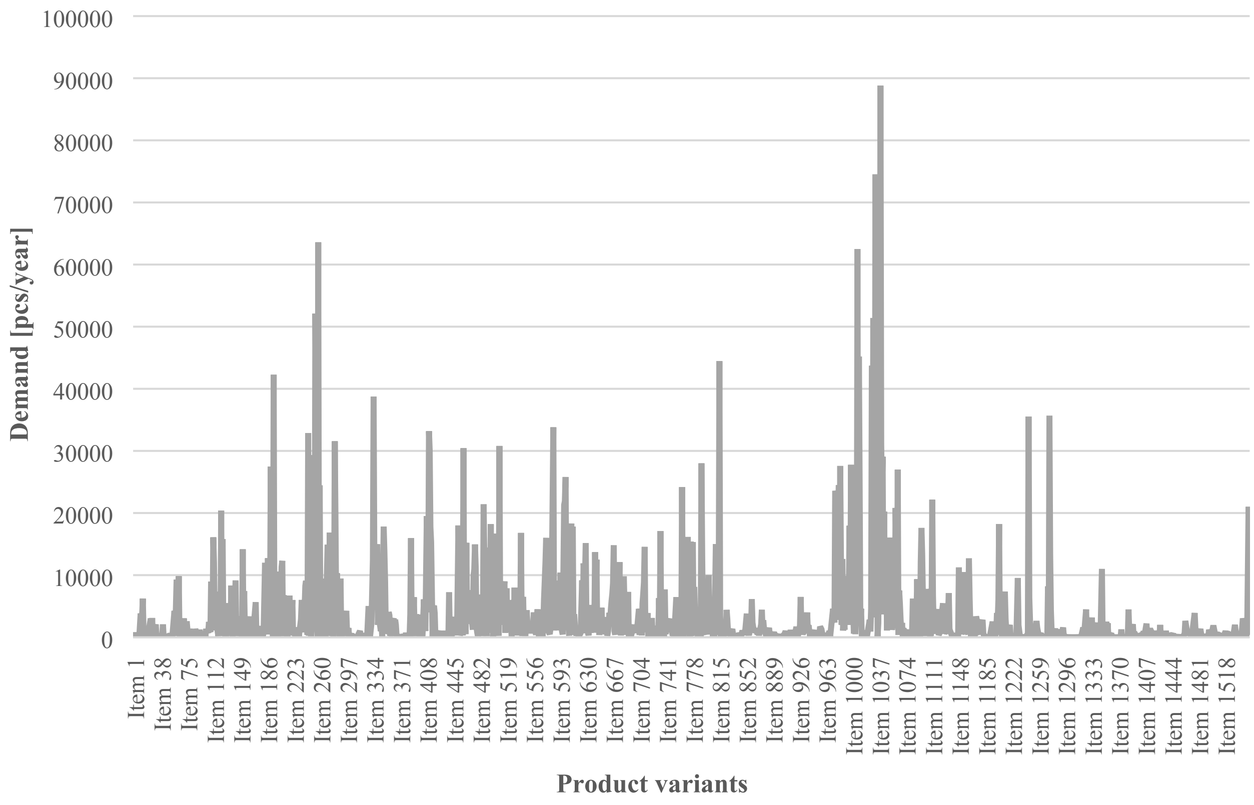

Figure 5. Annual product variants demand trend

The company stocks the products, after production of individual product variants, following the MTS strategy. The decision to implement such strategy has lead, as primary effect, to the occupation of a large storage space and high level of inventory. Since plastic valves produce a large proportion of company revenues and customers ask for medium volume batches of such products, the industrial company is looking to introduce product platforms for this family of valves to make it possible to delay products differentiation and manufacture and customize products platforms to order, hence, increasing operational efficiency and reducing production and storage costs.

4.1 Product family definition

Case studies found in literature use product families with limited number of product variants, each of which is typically made of few components. To address this deficiency, a very large products family is considered in this study. In particular, the family of valves consists of 16 models, each of which is available in different materials, sizes and colours. Figure 6 shows an example of one of these valves, including the BOM, the finished product and the components description. Thirty-eight (38) product variants exist, each of which is composed of a combination from 9 to 14 components, for a total of 93 components most of which are symmetric around the axis of insertion. The PCIM is the input to the MJPN algorithm for constructing the phylogenetic network. In the following sections, valve variants are indicated from P1 to P38 and the sub-components from C1 to C93.

Component number	*Component name*
1	Handle
2	Pin O-ring gasket
3	Pin
4	Body
5	PTFE gasket
6	Ball
7	Gasket supporting 5
8	Radial sealing O-ring gasket
9	Bush

Figure 6. Example of a valve variant and its components

4.2 Valves platform design and definition of assembly/disassembly relationships

The MJPN algorithm creates 18 consensus medians/platforms, indicated from Platform 1 to Platform 18. The assembly and disassembly relationships resulting from platforms reconfiguration are reported in the phylogenetic network tree (Figure 7) while the platforms composition is reported in Table 1.

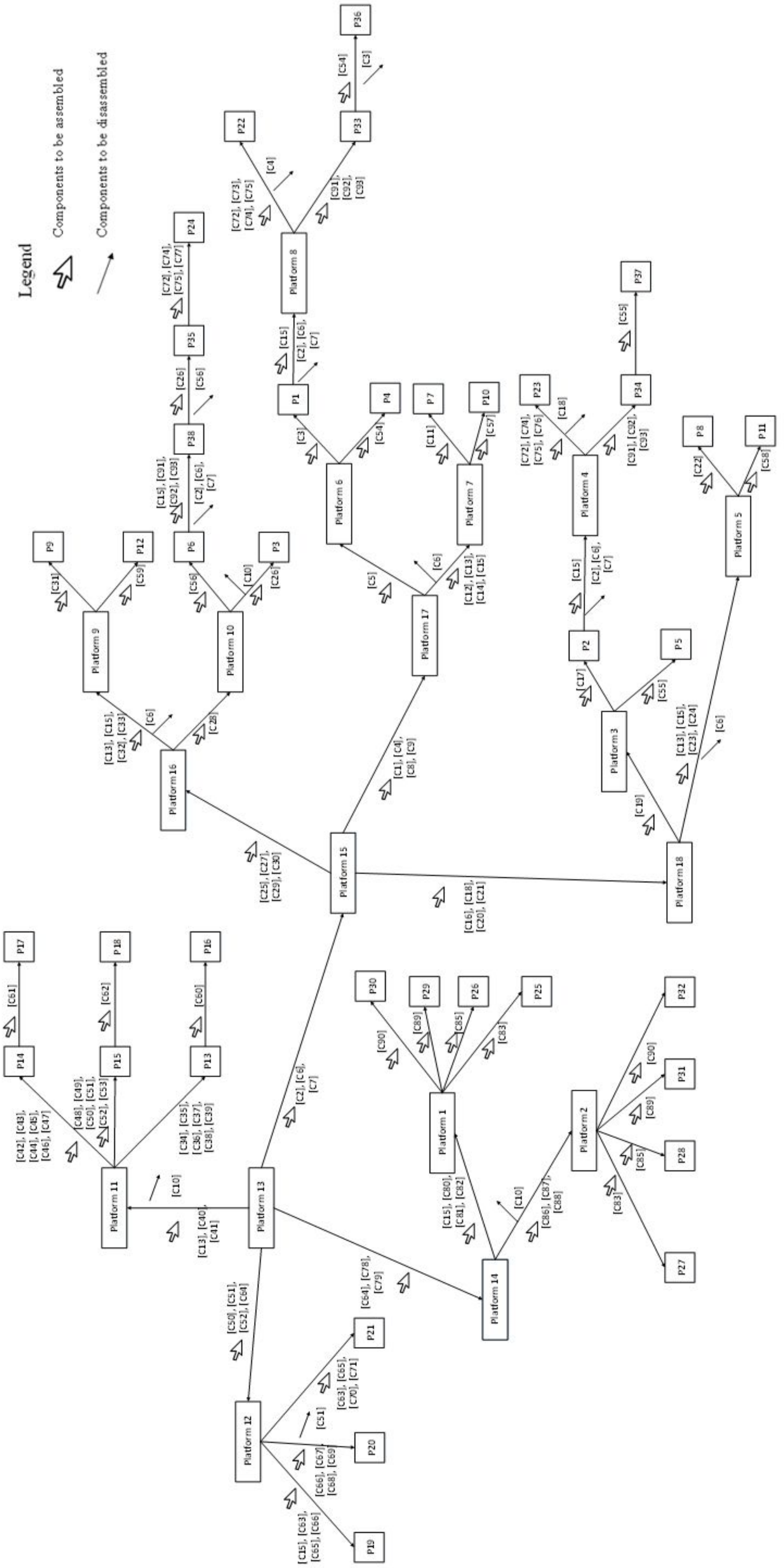

Figure 7. Phylogenetic network tree result for the family of plastic valves

Table 1. Plastic valves platforms composition

Platform	*Components*
Platform 1	C10, C15, C78, C79, C80, C81, C82, C84
Platform 2	C78, C79, C84, C86, C87, C88
Platform 3	C2, C6, C7, C10, C16, C18, C19, C20, C21
Platform 4	C10, C15, C16, C17, C18, C19, C20, C21
Platform 5	C2, C7, C10, C13, C15, C16, C18, C20, C21, C23, C24
Platform 6	C1, C2, C4, C5, C6, C7, C8, C9, C10
Platform 7	C1, C2, C4, C7, C8, C9, C10, C12, C13, C14, C15
Platform 8	C1, C3, C4, C5, C8, C9, C10, C15
Platform 9	C2, C7, C10, C13, C15, C25, C27, C29, C30, C32, C33
Platform 10	C2, C6, C7, C10, C25, C27, C28, C29, C30
Platform 11	C13, C40, C41
Platform 12	C10, C50, C51, C52, C64
Platform 13	C10
Platform 14	C10, C78, C79, C84
Platform 15	C2, C6, C7, C20
Platform 16	C2, C6, C7, C10, C25, C27, C29, C30
Platform 17	C1, C2, C4, C6, C7, C8, C9, C10
Platform 18	C2, C6, C7, C10, C16, C18, C20, C21

4.3 Platforms variety and platforms customization effort analysis

The phylogenetic tree obtained in Step II (Figure 7) is decomposed into multiple levels. In this case study, 7 levels result from tree decomposition (l = 1…7) and for all levels l = 1,…,6 platforms variety, PRI and PCI indices are computed. To determine the assembly customization indices (ACI) of the PCI, all the components involved in the assembly process are analyzed. In the manual handling phase, all these components can be grasped and manipulated by one hand without the aid of grasping tools, which corresponds to a digit value equal to 0. The second digit is determined considering that the components are easy to grasp and manipulate and their size is greater than 15 mm, hence, the corresponding digit code is 0. Therefore, the two-digits code for manual handling of each component is 00. For the manual insertion phase, a first digit code equal to 0 is selected since all the components and associated tools, including hands, can easily reach the desired insertion location. The second selected digit is 6 since holding down is required during subsequent processes to maintain orientation and stability at the location and no resistance occurs during insertion. The two-digits code for manual insertion of each component is 06, yielding an overall assembly effort for each component equal to (0+0)+(0+6)=6.

To evaluate the disassembly effort for the disassembly customization index (DCI), an UFI index equal to 6.12 is used for each component. Such value is defined by actually measuring the unit component disassembly time. This time is similar for all components since they have similar size and dimensions envelop, therefore, an average component disassembly time equal to 6.5 seconds is used. The corresponding UFI value, i.e. 6.12, is calculated by applying the following Equation 4, experimentally determined by Sodhi, Sonnenberg, and Das (2004):

$$\text{Unfastening time(s)} = 5 + 0.04 \cdot \text{UFI}^2 \qquad (4)$$

Table 2 shows a summary of the main results. Tables containing both the detailed and global values of the indices are included in Appendix 1.

Table 2. Indices for the L-1 levels of the phylogenetic tree

Level	*Formed platforms*	*N of components per platform*	*Platforms variety*	*Average components per platform*	*PRI*	*PCI*
Level 1	Plat13	1	1	1	0.94	21.97
Level 2	Plat11	3	4	4	0.75	18.71
	Plat12	5				
	Plat14	4				
	Plat15	4				
Level 3	P13	9	9	7.78	0.43	9.82
	P14	9				
	P15	9				
	Plat12	5				
	Plat1	8				
	Plat2	6				
	Plat16	8				
	Plat17	8				
	Plat18	8				
Level 4	P13	9	12	8.83	0.32	7.12
	P14	9				
	P15	9				
	Plat12	5				
	Plat1	8				
	Plat2	6				
	Plat9	11				
	Plat10	9				
	Plat6	9				
	Plat7	11				
	Plat3	9				
	Plat5	11				
Level 5	P13	9	15	8.87	0.2	4.20
	P14	9				

	P15	9				
	Plat12	5				
	Plat1	8				
	Plat2	6				
	Plat9	11				
	Plat10	9				
	P38	11				
	Plat6	9				
	Plat8	8				
	Plat7	11				
	Plat3	9				
	Plat4	8				
	Plat5	11				
	P13	9				
	P14	9				
	P15	9				
	Plat12	5				
	Plat1	8				
	Plat2	6				
	Plat9	11				
Level 6	Plat10	9	15	8.87	0.2	4.08
	P35	11				
	Plat6	9				
	Plat8	8				
	Plat7	11				
	Plat3	9				
	Plat4	8				
	Plat5	11				

Table 2 shows that exploring the tree from Level 1 to Level 6 the platforms variety increases from 1 to 15 as well as the average number of components per platform which increases from 1 to 8.87; while the platforms customization effort indicators decrease from 0.94 to 0.2 for PRI and from 21.97 to 4.08 for PCI.

The main results are in Figure 8 and Figure 9. In particular, Figure 8 shows the trend of the average number of components per platform (ACP) vs. PRI while Figure 9 shows the trend of platforms variety vs. PRI. The trends shown in these graphs indicate that as ACP and platforms variety increases PRI decreases. Similar trends are observed when plotting ACP and platforms variety vs. PCI.

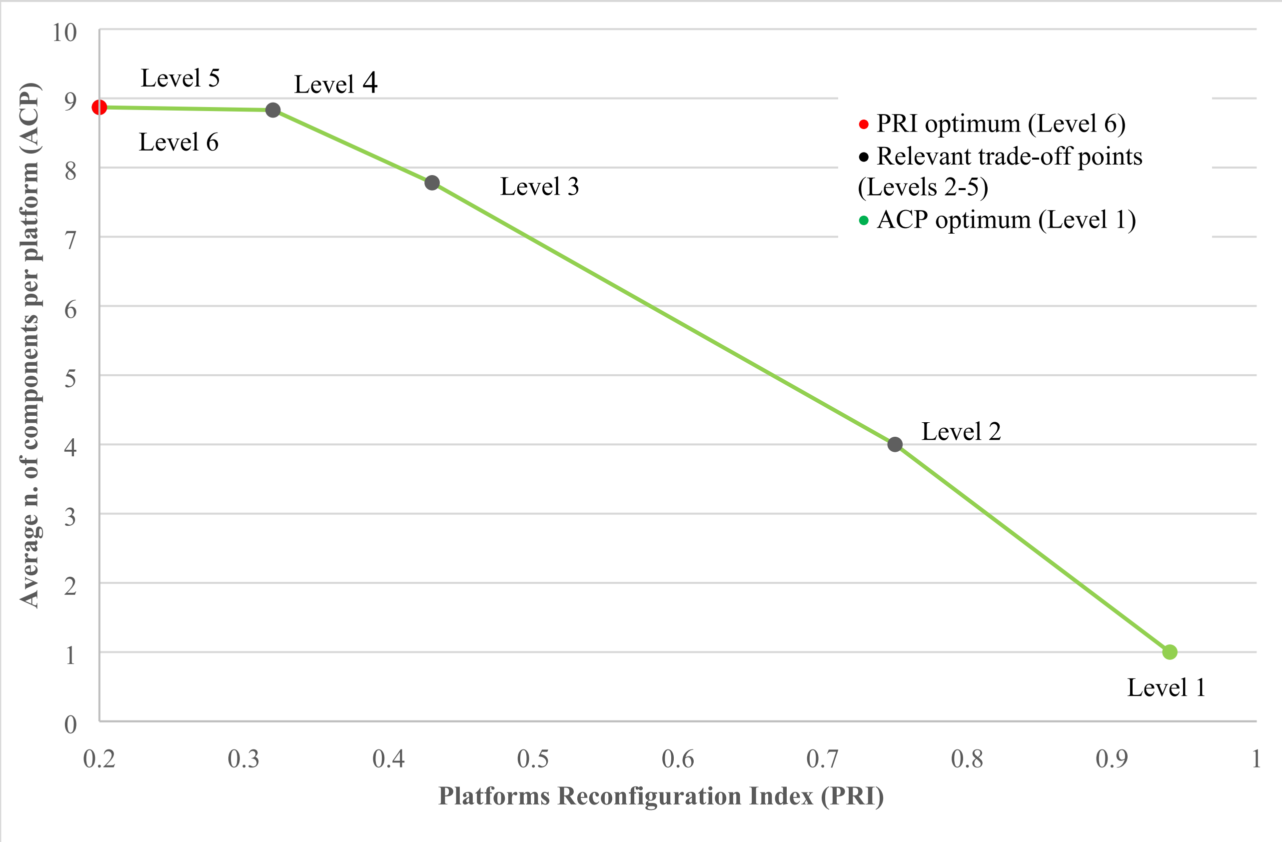

Figure 8. ACP vs. PRI trend

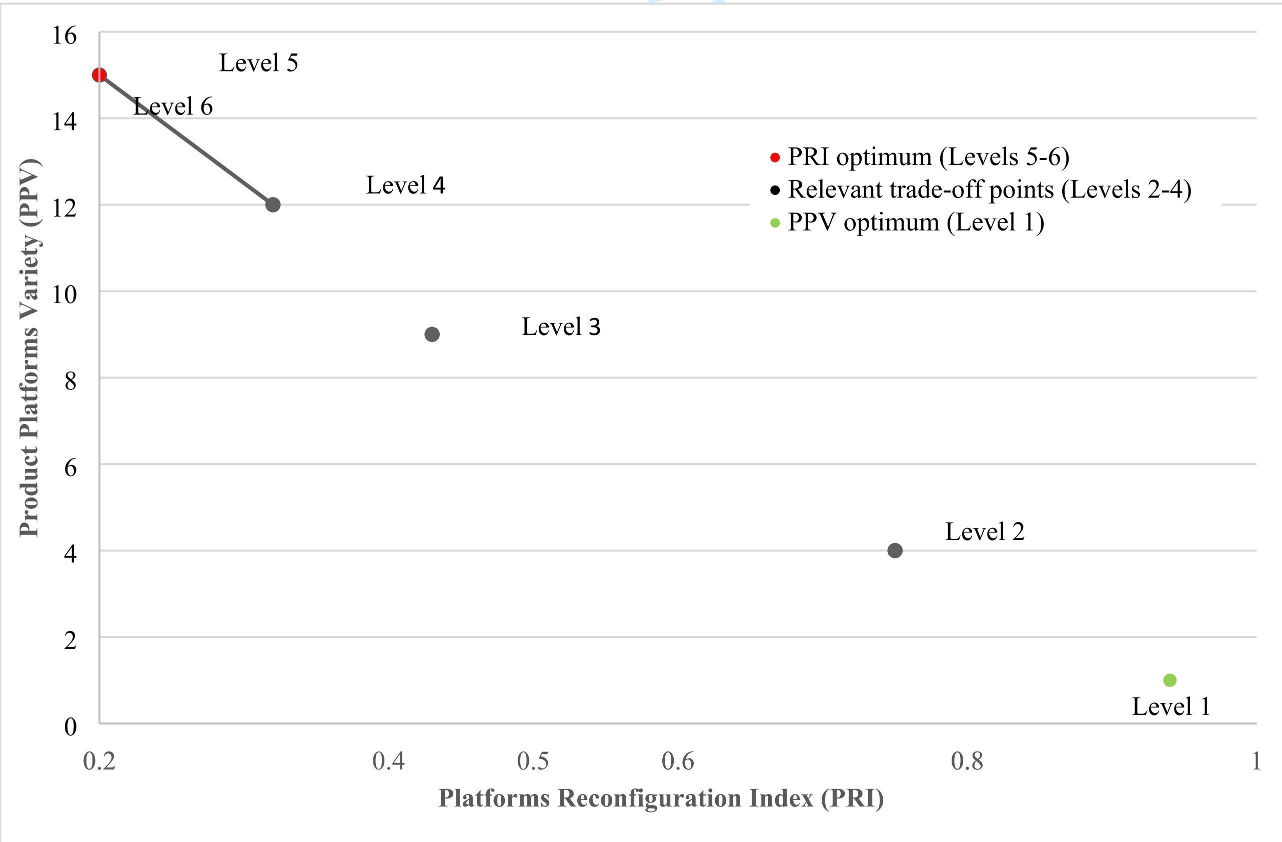

Figure 9. Platforms variety vs. PRI trend

4.4 Selection of best product platforms

The case company can select the platforms configuration that best meets its needs, having the values of platforms variety and platforms customization effort indices for each level of the phylogenetic network tree (Table 2). The considered case company aims at reducing the variety level, and consequently the inventory at the cost of acceptable increase of platforms customization effort in terms of number of the required assembly/disassembly tasks. For this reason, the platforms configuration from Level 6 is selected as a final solution. Figure 10 shows the product platforms (highlighted in grey) selected for mass production and storage prior to customization according to orders, as well as the assembly/disassembly relationships involved in subsequently producing each product reconfiguration.

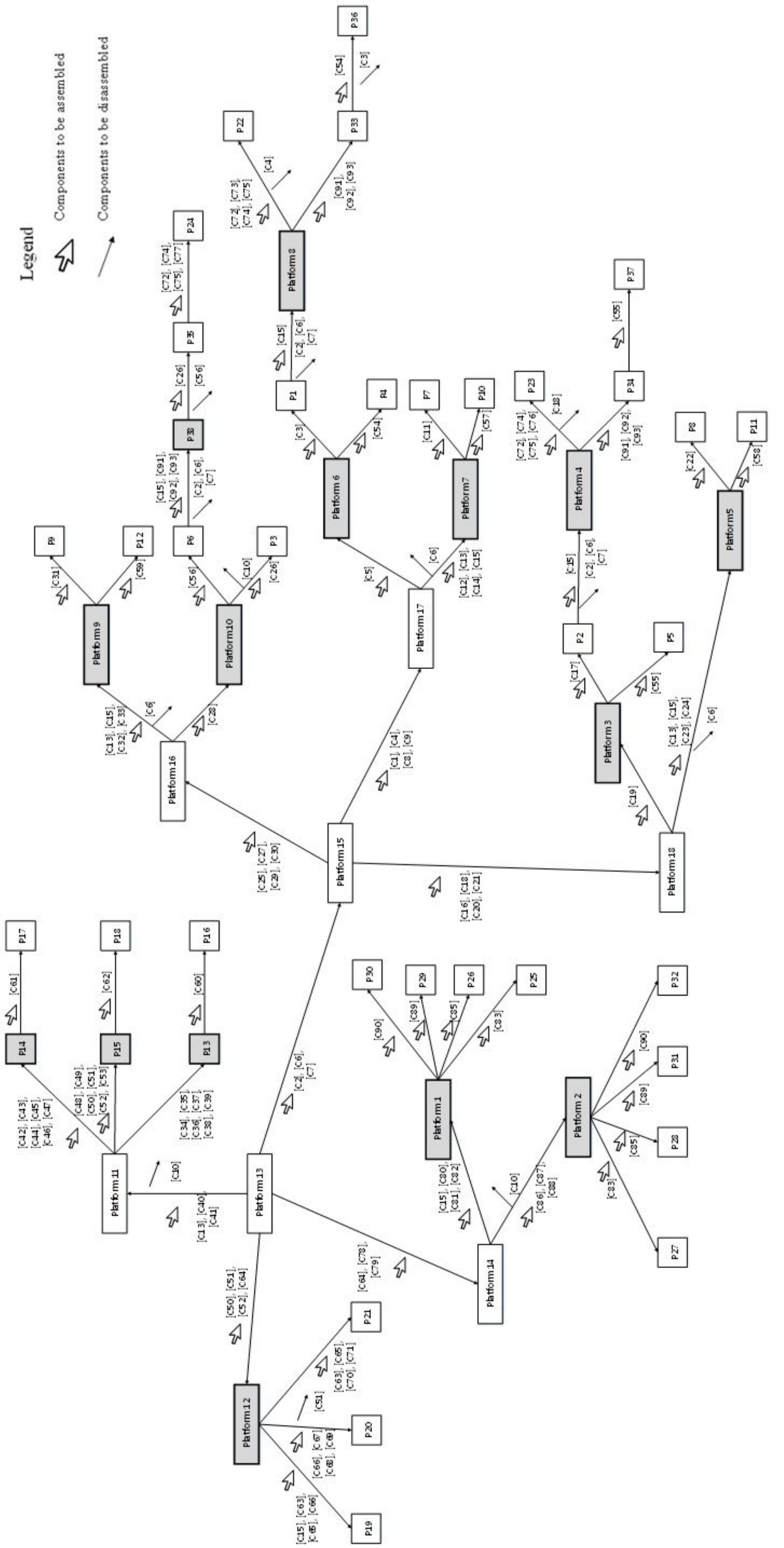

Figure 10. Final selection of product platforms

Compared to the current production strategy (MTS), in which the company stocks 38 types of valves, following the strategy suggested by the developed DSS, 15 valve platforms are selected for manufacture and storage leading to a reduction of 60.5% of product variety and consequently to significant savings in storage costs. The case company accepted an increase in platforms reconfiguration effort, represented by PRI and PCI indicators, of about 20% due to the platform reconfiguration required by the new production scenario compared to the MTS strategy. Individual final products were assembled and stocked in the company warehouse using the MTS strategy, while in the new proposed configuration based on DPD, only the platforms are stocked and reconfigured into the final products through assembly and disassembly operations as needed and shipped to customers, hence reducing warehouse storage and handling cost. The phylogenetic tree Level 6 selected by the case company corresponds to a value of PRI equal to 0.2, representing an increase of this index of about 20%. PRI and PCI indices are indicative of the cost of platform reconfiguration by assembly and disassembly. The selection of Level 6 leads to a slight increase of valves portfolio because the platforms themselves become new intermediate products that need to be managed. Nevertheless, the savings obtained in terms of storage costs and product variety reduction outweighed the reconfiguration effort increase.

The proposed DSS supports industrial companies in the transition towards the adoption of DPD by using product platforms providing detailed information about the platforms created in each level of reconfiguration together with the components involved in assembly and disassembly operations and the values of PRI and PCI indices, indicative of the cost of platform reconfiguration. Each level of the phylogenetic tree corresponds to a feasible DPD configuration and to a different trade-off between platform variety and platform reconfiguration effort which is an effective tool to guide industrial companies in the selection of the most suitable DPD configuration.

5. Conclusions

Dynamic market demands and changing customers' requirements and regulations are responsible for products variety proliferation. The use of product platforms is an effective strategy to manage the increasing variety and to delay products differentiation. This paper proposes an innovative decision support system (DSS) for product platforms design and selection to best manage the trade-off between platforms variety and number of assembly/disassembly tasks to be performed to transform a product platform into a product variant through platforms reconfiguration and customization efforts. The Median-Joining Phylogenetic Networks (MJPN) algorithm is used in the design and planning phases to define the number and composition of different platforms using both assembly and disassembly to customize the platforms into product variants as needed based on orders. The MJPN methodology is a widely used approach in biology but is relatively new in the manufacturing field. After the platforms design, the phylogenetic tree is decomposed into multiple levels to assist with platforms selection. New metrics to measure platforms customization effort by considering the required assembly/disassembly tasks, i.e. Platforms Reconfiguration Index (PRI), and the ease of assembly/disassembly factors, i.e. Platforms Customization Index (PCI), have been developed. They represent an important new contribution to the application of products platforms customization for managing variety in assembled products. In particular, such indices provide tools that support industrial companies in determining, for each product variant, whether it is better to adopt delay product differentiation (DPD) or assemble to order (ATO) strategy, and guide them in the selection of effective product platforms. A real case study of a large family of plastic valves is used to validate the proposed approach. The case studies found in literature involve small product families with limited number of products variants. In contrast, a family of thirty-eight (38) product variants is considered in this research. Each variant is composed of a combination of 9 to 14 components, for a total of 93 components. Results show that the developed DSS efficiently supports companies in the design and selection of effective platforms, leading to a reduction of the variety of assembled and stocked products of about 60.5% and to significant production and inventory efficiencies and cost savings. At the same time, the company accepted an increase of assembly/disassembly effort required for platforms customization by about 20% and an increase of valves portfolio, which is more than offset by the reduction in inventory cost. Using the MJPN and the assembly/disassembly modular product platforms offer the possibility to produce different products using more than one platform, providing more flexibility in production planning. The introduction of product platforms also helps companies achieve a more flexible response to the introduction of new products mix as well as increased adaptability to changing market demands. Future research deals with the inclusion of the annual demand data of the different product variants to consider its effect on the platforms design.

Acknowledgements

This research was conducted at the Intelligent Manufacturing Systems (IMS) Centre, University of Windsor, Canada. Case company data were elaborated at the University of Bologna, Italy.

Disclosure statement

No potential conflict of interest was reported by the Authors.

Funding

This work was supported by Canada Research Chairs (CRC); Natural Sciences and Engineering Research Council of Canada (NSERC); and Fondazione Cariparo (Cassa di Risparmio di Padova e Rovigo).

References

AlGeddawy, T., and H. ElMaraghy. 2010a. "Assembly Systems Layout Design Model for Delayed Products Differentiation." International Journal of Production Research 48 (18): 5281–5305.

AlGeddawy, T., and H. ElMaraghy. 2010b. "Design of Single Assembly Line for the Delayed Differentiation of Product Variants." Flexible Services and Manufacturing Journal 22 (3–4): 163–182.

Aljorephani, S., 2017, "Product Variants Platform Customization Strategies and Performance of Reconfigurable Manufacturing Systems (RMS)", MASc. Thesis, Intelligent Manufacturing Systems (IMS) Center, University of Windsor, Canada.

Bandelt, H. J., P. P. Forster, and A. A. Röhl. 1999. "Median-joining Networks for Inferring Intraspecific Phylogenies." Molecular Biology and Evolution 16 (1): 37–48.

Ben-Arieh, D., T. Easton, and A. M. Choubey. 2009. "Solving the Multiple Platforms Configuration Problem." International Journal of Production Research 47 (7): 1969–1988.

Blecker, T., and N. Abdelkafi. 2006. Mass Customization: State-of-the-art and Challenges Mass Customization: Challenges and Solutions,1-25. Springer.

Boothroyd, G., and L. Alting. 1992. "Design for Assembly and Disassembly." CIRPAnnals 41 (2): 625–636.

Boothroyd, G., P. Dewhurst, and W. A. Knight. 2001. "Product design for manufacture and assembly." CRC Press.

Bortolini, M., F. G. Galizia, and C. Mora. 2018. "Reconfigurable manufacturing systems: literature review and research trend." Journal of Manufacturing Systems 49: 93–106.

Bryan, A., J. Ko, S. Hu, and Y. Koren. 2007. "Co-evolution of Product Families and Assembly Systems." CIRP Annals 56 (1): 41–44.

Fluxus-engineering.com. 2012. "Free Phylogenetic Network Software." http://www.fluxus-engineering.com.

Gilmore, J. H. (1997). "The four faces of mass customization." Harvard business review 75 (1): 91-101.

Gupta, D., and S. Benjaafar. 2004. "Make-to-order, make-to-stock, or delay product differentiation? A common framework for modeling and analysis." IIE transactions 36 (6): 529-546.

Hanafy, M., and H. ElMaraghy. 2015. "Developing assembly line layout for delayed product differentiation using phylogenetic networks." International Journal of Production Research 53 (9): 2633-2651.

He, D., and A. Babayan. 2002. "Scheduling manufacturing systems for delayed product differentiation in agile manufacturing." International Journal of Production Research 40 (11): 2461-2481.

He, D., A. Kusiak, and T. L. B. Tseng. 1998. "Delayed Product Differentiation: A Design and Manufacturing Perspective." Computer Aided Design 30 (2): 105–113.

Hsu, H. M., and W. P. Wang. 2004. "Dynamic programming for delayed product differentiation." European Journal of Operational Research 156 (1): 183-193.

Huson, D. H., and C. Scornavacca. 2011. "A Survey of Combinatorial Methods for Phylogenetic Networks." Genome Biology and Evolution 3: 23–35.

Jose, A., and M. Tollenaere. 2005. "Modular and platform methods for product family design: literature analysis." Journal of Intelligent Manufacturing 16 (3): 371-390.

Khajavirad, A., J. J. Michalek, and T. W. Simpson. 2009. "An efficient decomposed multi-objective genetic algorithm for solving the joint product platform selection and product family design problem with generalized commonality." Structural and Multidisciplinary Optimization 39 (2): 187-201.

Ko, J., and S. Jack. Hu. 2008. "Balancing of manufacturing systems with complex configurations for delayed product differentiation." International Journal of Production Research 46 (15): 4285-4308.

Kroll, E., and B. Carver. 1999. "Disassembly Analysis through Time Estimation and Other Metrics." Robotics and Computer-Integrated Manufacturing 15 (3): 191–200.

Lee, B., and K. Ishii. 1997. "Demanufacturing Complexity Metrics in Design for Recyclability." In Proceedings of the 1997 IEEE International Symposium on Electronics and the Environment, San Francisco, CA.

Mesa, J., H. Maury, R. Arrieta, A. Bula, and C. Riba. 2015. "Characterization of modular architecture principles towards reconfiguration: a first approach in its selection process." The International Journal of Advanced Manufacturing Technology 80 (1-4): 221-232.

Mesa, J. A., I. Esparragoza, and H. Maury. 2017. "Development of a metric to assess the complexity of assembly/disassembly tasks in open architecture products." International Journal of Production Research 1-19.

Mesa, J., H. Maury, J. Turizo, and A. Bula. 2014. "A methodology to define a reconfigurable system architecture for a compact heat exchanger assembly machine." The International Journal of Advanced Manufacturing Technology 70 (9-12): 2199-2210.

Meyer, M. H. 1997. "Revitalize your product lines through continuous platform renewal." Research Technology Management 40 (2): 17–28.

Meyer, M., and A. P. Lehnerd. 1997. The Power of Product Platform – Building Value and Cost Leadership. New York: Free Press. Montreuil, B. 1999. "Fractal Layout Organization for Job Shop Environments." International Journal of Production Research 37 (3): 501–521.

Miller, M., J. Summers, J. Mathieson, and G. Mocko. 2012. "Manufacturing Assemby Time Estimation Using Structural Complexity Metric Trained Artificial Neural Networks." Journal of Computing and Information Science in Engineering 14 (1): 011005-1– 011005-10.

Moon, S. K., J. Park, T. Simpson, and S. R. T. Kumara. 2008. "A dynamic multi-agent system based on a negotiation mechanism for product family design." IEEE Transactions on Automation Science and Engineering 5 (2): 234-244.

Olhager, J., and D. I. Prajogo. 2012. "The impact of manufacturing and supply chain improvement initiatives: A survey comparing make-to-order and make-to-stock firms." Omega 40 (2): 159-165.

Orfi, N., J. Terpenny, and A. Sahin-Sariisik. 2011. "Harnessing Product Complexity: Step 1 – Establishing Product Complexity Dimensions and Indicators." The Engineering Economist 56 (1): 59–79.

Rafiei, H., and M. Rabbani. 2012. "Capacity coordination in hybrid make-to-stock/make-to-order production environments." International Journal of Production Research 50 (3): 773-789.

Rajagopalan, S. (2002). "Make to order or make to stock: model and application." Management Science 48 (2): 241-256.

Rodriguez-Toro, C., S. Tate, G. Jared, and K. Swift. 2003. "Complexity Metrics for Design (Simplicity + Simplicity = Complexity)." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 217: 721–725.

Samy, S., and H. ElMaraghy. 2010. "A Model for Measuring Products Assembly Complexity." International Journal of Computer Integrated Manufacturing 23 (11): 1015–1027.

Sanderson, S., and M. Uzumeri. 1995. "Managing product families: the case of the Sony Walkman." Research Policy 24 (5): 761–782.

Shou, T., Y. Li, Y. W. Park, and M. Kang. 2017. "The impact of product complexity and variety on supply chain integration." International Journal of Physical Distribution & Logistics Management 47 (4): 297–317.

Simpson, T. W., Z. Siddique, and R. J. Jiao. 2006. "Product platform and product family design: methods and applications." Springer Science & Business Media.

Sodhi, R., M. Sonnenberg, and S. Das. 2004. "Evaluating the unfastening effort in design for disassembly and serviceability." Journal of Engineering Design 15 (1): 69-90.

Swaminathan, J. M., and S. R. Tayur. 1998. "Managing Broader Product Lines through Delayed Differentiation Using Vanilla Boxes." Management Science 44 (12): 161–172.

Thevenot, H. J., and T. W. Simpson. 2006. "Commonality indices for product family design: a detailed comparison." Journal of Engineering Design 17 (2): 99-119.

Williams, C. B., J. K. Allen, D. W. Rosen, and F. Mistree. 2007. "Designing platforms for customizable products and processes in markets of non-uniform demand." Concurrent Engineering: Research and Applications 201-216.

Yang, B., N. D. Burns, and C. J. Backhouse. 2004. "Postponement: a review and an integrated framework." International Journal of Operations & Production Management 24 (5): 468-487.

Yu, Y., A. A. Yassine, and D. E. Goldberg. 2007. "An information theoretic method for developing modular architectures using genetic algorithms." Research in Engineering Design 18 (2):91-109.

Zinn, W., and D. J. Bowersox. 1988. "Planning Physical Distribution with the Principle of Postponement." Journal of Business Logistics 9 (2).

Appendix 1

Table A1. PRI values for Level 1 of the plastic valves phylogenetic tree.

Reconfigurations	*Assembly tasks*	*NCApv*	*Disassembly tasks*	*NCDpv*	*NCVv*	*Strategy*	*PRIvp*
Plat 13 - P1	C1-C2-C3-C4-C5-C6-C7-C8-C9	9	-	0	10	DPD	0.9
Plat 13 - P2	C2-C6-C7-C16-C17-C18-C19-C20-C21	9	-	0	10	DPD	0.9
Plat 13 - P3	C2-C6-C7-C25-C26-C27-C28-C29-C30	9	C10	1	9	ATO	1
Plat 13 - P4	C1-C2-C4-C5-C6-C7-C8-C9-C54	9	-	0	10	DPD	0.9
Plat 13 - P5	C2-C6-C7-C16-C18-C19-C20-C21-C55	9	-	0	10	DPD	0.9
Plat 13 - P6	C2-C6-C7-C25-C27-C28-C29-C30-C56	9	-	0	10	DPD	0.9
Plat 13 - P7	C1-C2-C4-C7-C8-C9-C11-C12-C13-C14-C15	11	-	0	12	DPD	0.92
Plat 13 - P8	C2-C7-C13-C15-C16-C18-C20-C21-C22-C23-C24	11	-	0	12	DPD	0.92
Plat 13 - P9	C2-C7-C13-C15-C25-C27-C29-C30-C31-C32-C33	11	-	0	12	DPD	0.92
Plat 13 - P10	C1-C2-C4-C7-C8-C9-C12-C13-C14-C15-C57	11	-	0	12	DPD	0.92
Plat 13 - P11	C2-C7-C13-C15-C16-C18-C20-C21-C23-C24-C58	11	-	0	12	DPD	0.92
Plat 13 - P12	C2-C7-C13-C15-C25-C27-C29-C30-C32-C33-C59	11	-	0	12	DPD	0.92
Plat 13 - P13	C13-C34-C35-C36-C37-C38-C39-C40-C41	9	C10	1	9	ATO	1
Plat 13 - P14	C13-C40-C41-C42-C43-C44-C45-C46-C47	9	C10	1	9	ATO	1
Plat 13 - P15	C13-C40-C41-C48-C49-C50-C51-C52-C53	9	C10	1	9	ATO	1
Plat 13 - P16	C13-C34-C35-C36-C37-C38-C39-C40-C41-C60	10	C10	1	10	ATO	1
Plat 13 - P17	C13-C40-C41-C42-C43-C44-C45-C46-C47-C61	10	C10	1	10	ATO	1

Plat 13 - P18	C13-C40-C41-C48-C49-C50-C51-C52-C53-C62	10	C10	1	10	ATO	1
Plat 13 - P19	C15-C50-C51-C52-C63-C64-C65-C66	8	-	0	9	DPD	0.89
Plat 13 - P20	C50-C52-C64-C66-C67-C68-C69	7	-	0	8	DPD	0.88
Plat 13 - P21	C50-C51-C52-C63-C64-C65-C70-C71	8	-	0	9	DPD	0.89
Plat 13 - P22	C1-C3-C5-C8-C9-C15-C72-C74-C75-C77	10	-	0	11	DPD	0.91
Plat 13 - P23	C15-C16-C17-C19-C20-C21-C72-C74-C75-C76	10	-	0	11	DPD	0.91
Plat 13 - P24	C15-C25-C26-C27-C28-C29-C30-C72-C74-C75-C77-C91-C92-C93	14	-	0	14	ATO	1
Plat 13 - P25	C15-C64-C78-C79-C80-C81-C82-C83	8	-	0	9	DPD	0.89
Plat 13 - P26	C15-C64-C78-C79-C80-C81-C82-C85	8	-	0	9	DPD	0.89
Plat 13 - P27	C64-C78-C79-C83-C86-C87-C88	7	C10	1	7	ATO	1
Plat 13 - P28	C64-C78-C79-C85-C86-C87-C88	7	C10	1	7	ATO	1
Plat 13 - P29	C15-C64-C78-C79-C80-C81-C82-C89	8	-	0	9	DPD	0.89
Plat 13 - P30	C15-C64-C78-C79-C80-C81-C82-C90	8	-	0	9	DPD	0.89
Plat 13 - P31	C64-C78-C79-C86-C87-C88-C89	7	C10	1	7	ATO	1
Plat 13 - P32	C64-C78-C79-C86-C87-C88-C90	7	C10	1	7	ATO	1
Plat 13 - P33	C1-C3-C4-C5-C8-C9-C15-C91-C92-C93	10	-	0	11	DPD	0.91
Plat 13 - P34	C15-C16-C17-C18-C19-C20-C21-C91-C92-C93	10	-	0	11	DPD	0.91
Plat 13 - P35	C15-C25-C26-C27-C28-C29-C30-C91-C92-C93	10	-	0	11	DPD	0.91
Plat 13 - P36	C1-C4-C5-C8-C9-C15-C54-C91-C92-C93	10	-	0	11	DPD	0.91
Plat 13 - P37	C15-C16-C17-C18-C19-C20-C21-C55-C91-C92-C93	11	-	0	11	ATO	1
Plat 13 - P38	C15-C25-C27-C28-C29-C30-C56-C91-C92-C93	10	-	0	11	DPD	0.91
						PRI	*0.94*
Product platform variety							*1*

Table A2. PCI values for Level 1 of the plastic valves phylogenetic tree.

Reconfigurations	*Assembly tasks*	*MH*	*I*	*sumACIcpv*	*Disassembly tasks*	*sumDCIcpv*	*PCIvp*
Plat 13 - P1	C1-C2-C3-C4-C5-C6-C7-C8-C9	00	06	54	-	0	54
Plat 13 - P2	C2-C6-C7-C16-C17-C18-C19-C20-C21	00	06	54	-	0	54
Plat 13 - P3	C2-C6-C7-C25-C26-C27-C28-C29-C30	00	06	54	C10	6.12	60.12
Plat 13 - P4	C1-C2-C4-C5-C6-C7-C8-C9-C54	00	06	54	-	0	54
Plat 13 - P5	C2-C6-C7-C16-C18-C19-C20-C21-C55	00	06	54	-	0	54
Plat 13 - P6	C2-C6-C7-C25-C27-C28-C29-C30-C56	00	06	54	-	0	54
Plat 13 - P7	C1-C2-C4-C7-C8-C9-C11-C12-C13-C14-C15	00	06	66	-	0	66
Plat 13 - P8	C2-C7-C13-C15-C16-C18-C20-C21-C22-C23-C24	00	06	66	-	0	66
Plat 13 - P9	C2-C7-C13-C15-C25-C27-C29-C30-C31-C32-C33	00	06	66	-	0	66
Plat 13 - P10	C1-C2-C4-C7-C8-C9-C12-C13-C14-C15-C57	00	06	66	-	0	66
Plat 13 - P11	C2-C7-C13-C15-C16-C18-C20-C21-C23-C24-C58	00	06	66	-	0	66
Plat 13 - P12	C2-C7-C13-C15-C25-C27-C29-C30-C32-C33-C59	00	06	66	-	0	66
Plat 13 - P13	C13-C34-C35-C36-C37-C38-C39-C40-C41	00	06	54	C10	6.12	60.12
Plat 13 - P14	C13-C40-C41-C42-C43-C44-C45-C46-C47	00	06	54	C10	6.12	60.12
Plat 13 - P15	C13-C40-C41-C48-C49-C50-C51-C52-C53	00	06	54	C10	6.12	60.12
Plat 13 - P16	C13-C34-C35-C36-C37-C38-C39-C40-C41-C60	00	06	60	C10	6.12	66.12
Plat 13 - P17	C13-C40-C41-C42-C43-C44-C45-C46-C47-C61	00	06	60	C10	6.12	66.12
Plat 13 - P18	C13-C40-C41-C48-C49-C50-C51-C52-C53-C62	00	06	60	C10	6.12	66.12

Plat 13 - P19	C15-C50-C51-C52-C63-C64-C65-C66	00	06	48	-	0	48
Plat 13 - P20	C50-C52-C64-C66-C67-C68-C69	00	06	42	-	0	42
Plat 13 - P21	C50-C51-C52-C63-C64-C65-C70-C71	00	06	48	-	0	48
Plat 13 - P22	C1-C3-C5-C8-C9-C15-C72-C74-C75-C77	00	06	60	-	0	60
Plat 13 - P23	C15-C16-C17-C19-C20-C21-C72-C74-C75-C76	00	06	60	-	0	60
Plat 13 - P24	C15-C25-C26-C27-C28-C29-C30-C72-C74-C75-C77-C91-C92-C93	00	06	84	-	0	84
Plat 13 - P25	C15-C64-C78-C79-C80-C81-C82-C83	00	06	48	-	0	48
Plat 13 - P26	C15-C64-C78-C79-C80-C81-C82-C85	00	06	48	-	0	48
Plat 13 - P27	C64-C78-C79-C83-C86-C87-C88	00	06	42	C10	6.12	48.12
Plat 13 - P28	C64-C78-C79-C85-C86-C87-C88	00	06	42	C10	6.12	48.12
Plat 13 - P29	C15-C64-C78-C79-C80-C81-C82-C89	00	06	48	-	0	48
Plat 13 - P30	C15-C64-C78-C79-C80-C81-C82-C90	00	06	48	-	0	48
Plat 13 - P31	C64-C78-C79-C86-C87-C88-C89	00	06	42	C10	6.12	48.12
Plat 13 - P32	C64-C78-C79-C86-C87-C88-C90	00	06	42	C10	6.12	48.12
Plat 13 - P33	C1-C3-C4-C5-C8-C9-C15-C91-C92-C93	00	06	60	-	0	60
Plat 13 - P34	C15-C16-C17-C18-C19-C20-C21-C91-C92-C93	00	06	60	-	0	60
Plat 13 - P35	C15-C25-C26-C27-C28-C29-C30-C91-C92-C93	00	06	60	-	0	60
Plat 13 - P36	C1-C4-C5-C8-C9-C15-C54-C91-C92-C93	00	06	60	-	0	60
Plat 13 - P37	C15-C16-C17-C18-C19-C20-C21-C55-C91-C92-C93	00	06	66	-	0	66
Plat 13 - P38	C15-C25-C27-C28-C29-C30-C56-C91-C92-C93	00	06	60	-	0	60

PCI	*21.97*

MH = Material Handling two-digit code; I = Insertion two-digits code.