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

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## 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

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3 al 2010). In this scenario, companies are switching from Make-To-Stock (MTS) and Make-To-Order (MTO)  
4 strategies to Delay Product Differentiation (DPD) in order to implement mass customization. DPD is a hybrid  
5 strategy that strives to reconcile the dual needs of high-variety and quick response time, by utilizing the concept  
6 of product platforms (Gupta and Benjaafar 2004). A product platform is defined as a set of sub-systems and  
7 interfaces that form a common structure from which a stream of derivative product variants can be efficiently  
8 produced and developed (Meyer and Lehnerd (1997); Simpson, Siddique and Jiao (2006)). In particular, a  
9 common product platform is manufactured to stock (MTS) in the first stage of production which is then  
10 differentiated into different products after demand is known in the second stage, i.e. manufactured to order  
11 (MTO) (Gupta and Benjaafar 2004). A large number of industrial companies introduced product platforms as  
12 tool to reach the benefits of DPD. Sony, for the development of the Walkman (Sanderson and Uzumeri 1995),  
13 Kodak, Black & Decker (Simpson, Siddique and Jiao 2006) and Hewlett-Packard (Meyer 1997) are among the  
14 most relevant applications.

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

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

## 57 58 59 60 **2. Literature review**

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3 This section is organized into two parts. The former explores the DPD concept and the methods and techniques  
4 used for product platforms design, and the latter introduces metrics and indices developed to model the  
5 assembly and disassembly tasks, which represent the two operations to perform in order to customize a  
6 platform into a variant.  
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### 9 10 **2.1 Delayed product differentiation and product platform concept**

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

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

## 34 **2.2 Effort in assembly/disassembly tasks**

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

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

### 44 45 46 47 48 49 **3. A decision support system for product platforms design and selection**

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51 In this paper, a decision support system (DSS) is proposed to guide industrial companies and practitioners in  
52 the design and selection of efficient product platforms, managing the trade-off between platforms variety and  
53 required platforms customization effort represented by the time and difficulty of assembly and disassembly  
54 tasks. Product platforms are designed by applying the Median Joining Phylogenetic Networks (MJPN). This  
55 methodology is traditionally used in biology and its use in the manufacturing and assembly field is relatively  
56 new. In particular, it is used in the design phase to define the number and composition of different platforms  
57 using both assembly and disassembly to customize the platforms into product variants as needed. In the  
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3 proposed DSS, it is assumed that components can be disassembled without damage (e.g. fastening), hence,  
4 preserving product quality integrity during platforms reconfiguration.  
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### 6 7 **3.1 Methodology**

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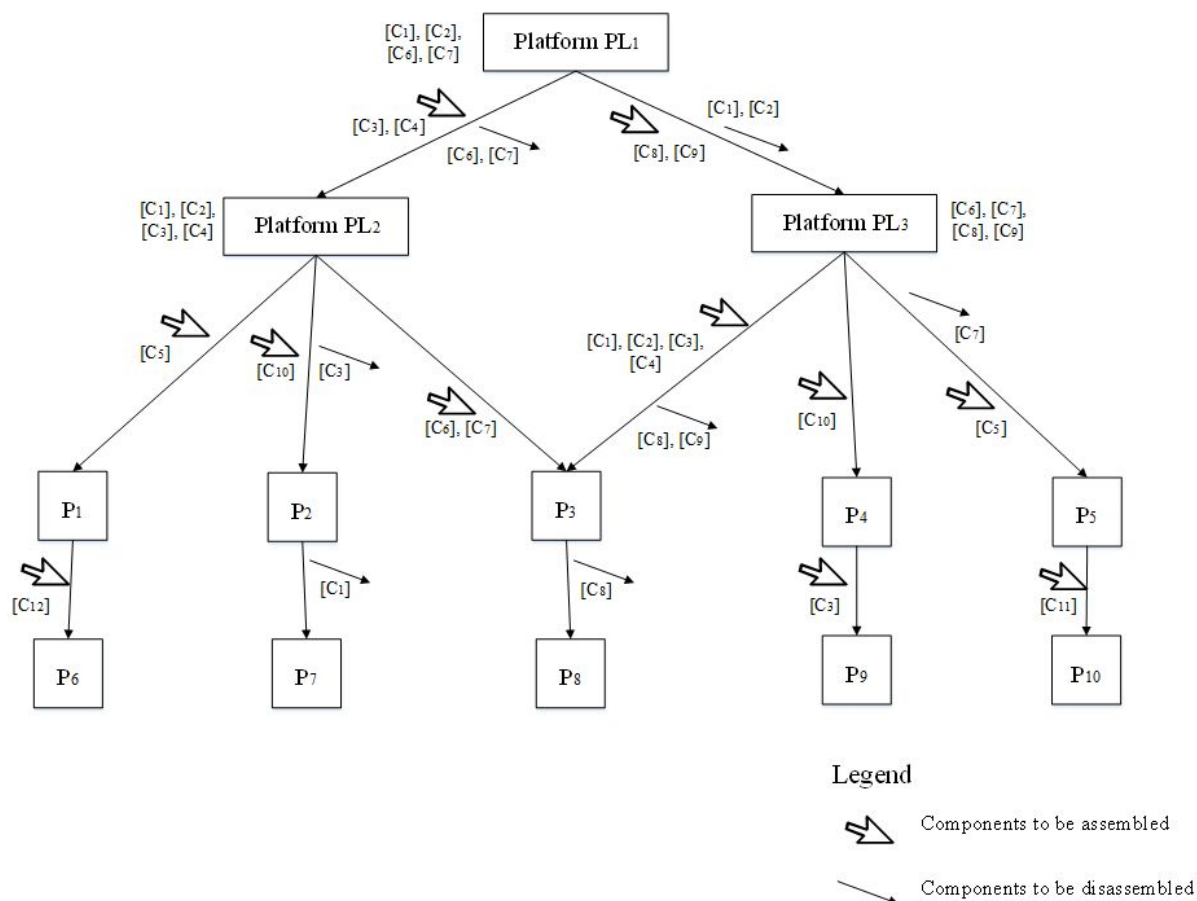


Figure 1. Example of phylogenetic network tree for a product family and its variants and components

In the example shown in Figure 1, the product family is composed of ten product variants (indicated from P1 to P10) and of a total number of twelve components (indicated from C1 to C12). The MJPN algorithm creates three product platforms (indicated from PL1 to PL3) 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



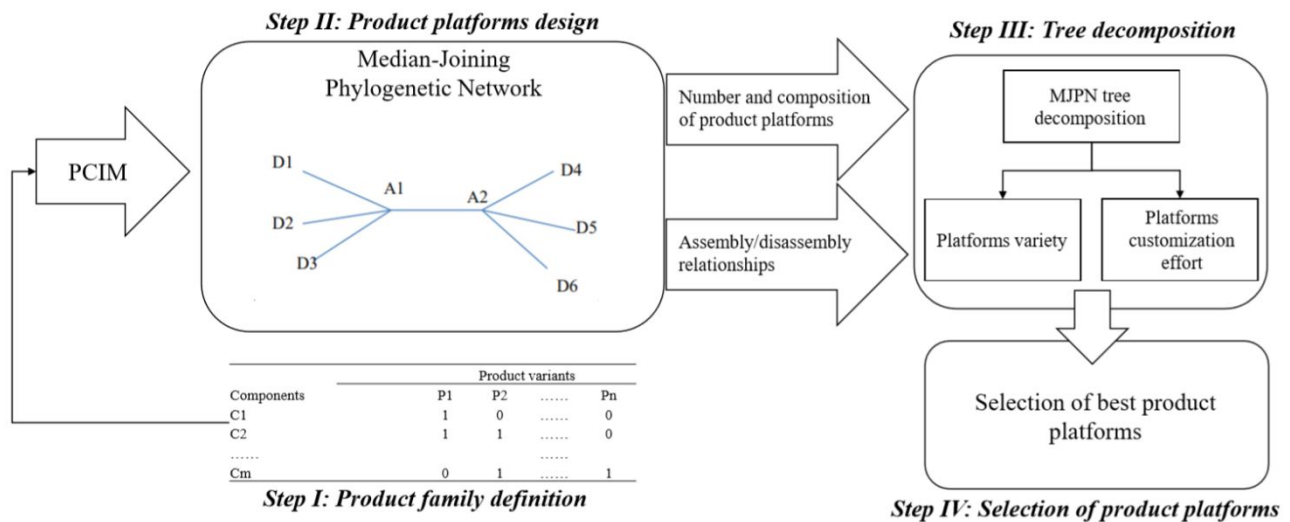


Figure 2. Schematic of the proposed decision support system (DSS)

### 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:

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

### 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 (PL<sub>1</sub> in the reference example), while a platform or a product variant belongs to level L if it does not have outgoing arrows (from P<sub>6</sub> to P<sub>10</sub> in the referenced example).

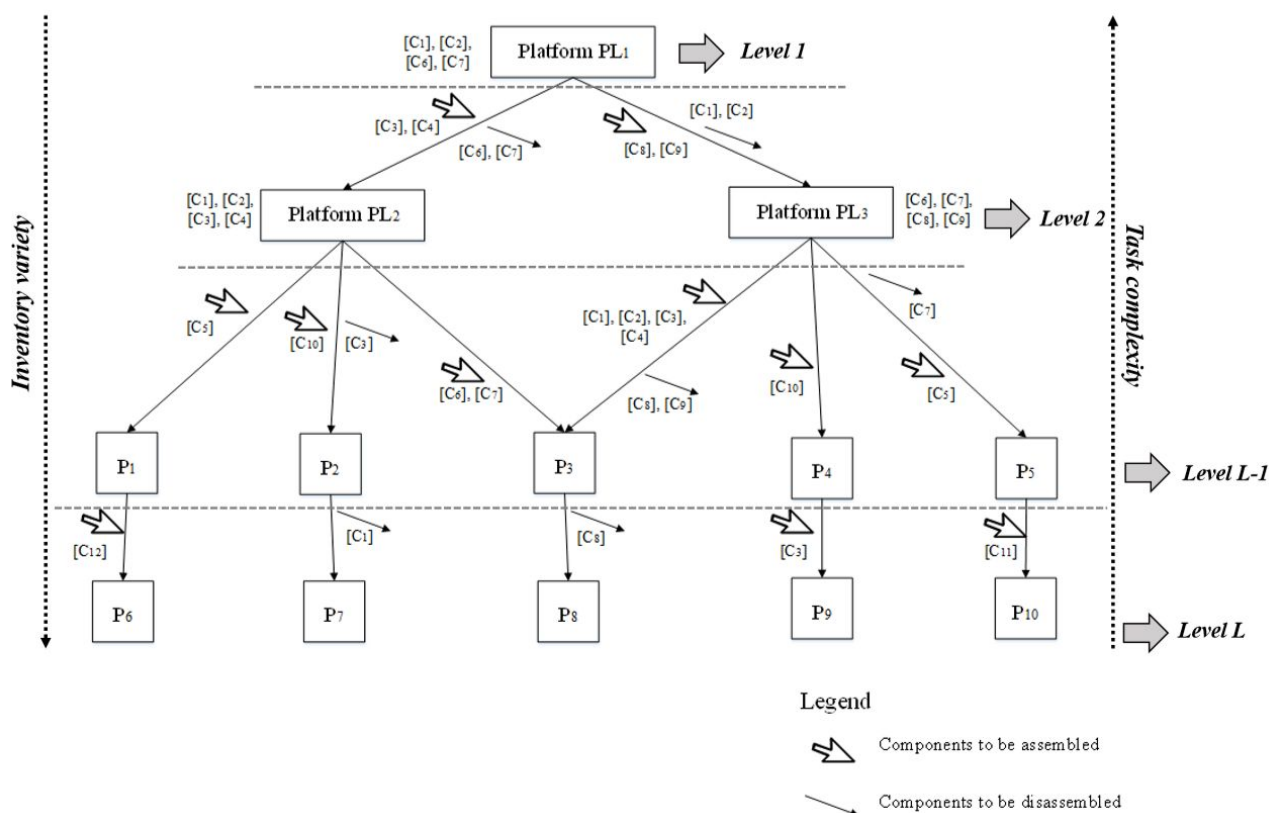


Figure 3. MJPN tree decomposition for platforms selection

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 ( $l = 1 \dots L$ );
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 $v = 1, \dots, V$
p	product platform $p = 1, \dots, P$

#### 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:

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

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  $0 \leq \text{PRI}_{vp} \leq 1$ .  $\text{PRI}_{vp}$  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:

$$\text{PRI} = \frac{\sum_{v=1}^V \text{PRI}_{vp}}{V} \quad (2)$$

### *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

$\text{ACI}_{cpv}$	assembly customization index (handling and insertion two-digit codes for assembly of component c to platform p to get variant v)
$\text{DCI}_{cpv}$	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  $l = 1, \dots, L - 1$  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.

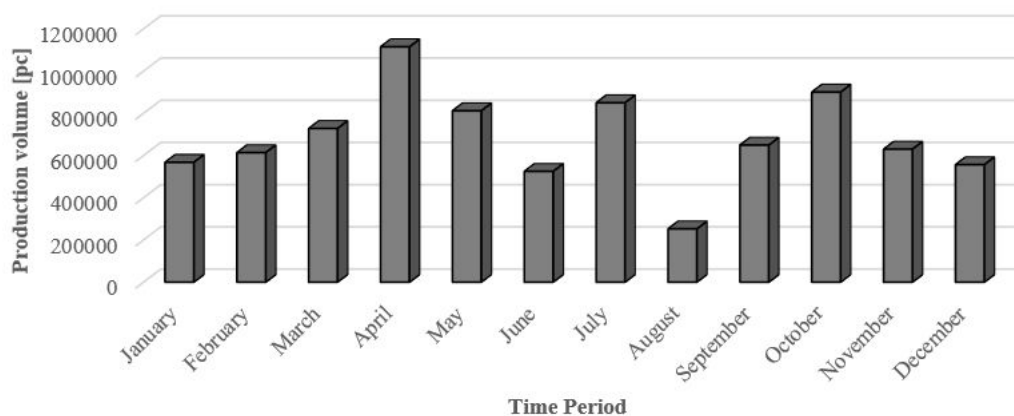
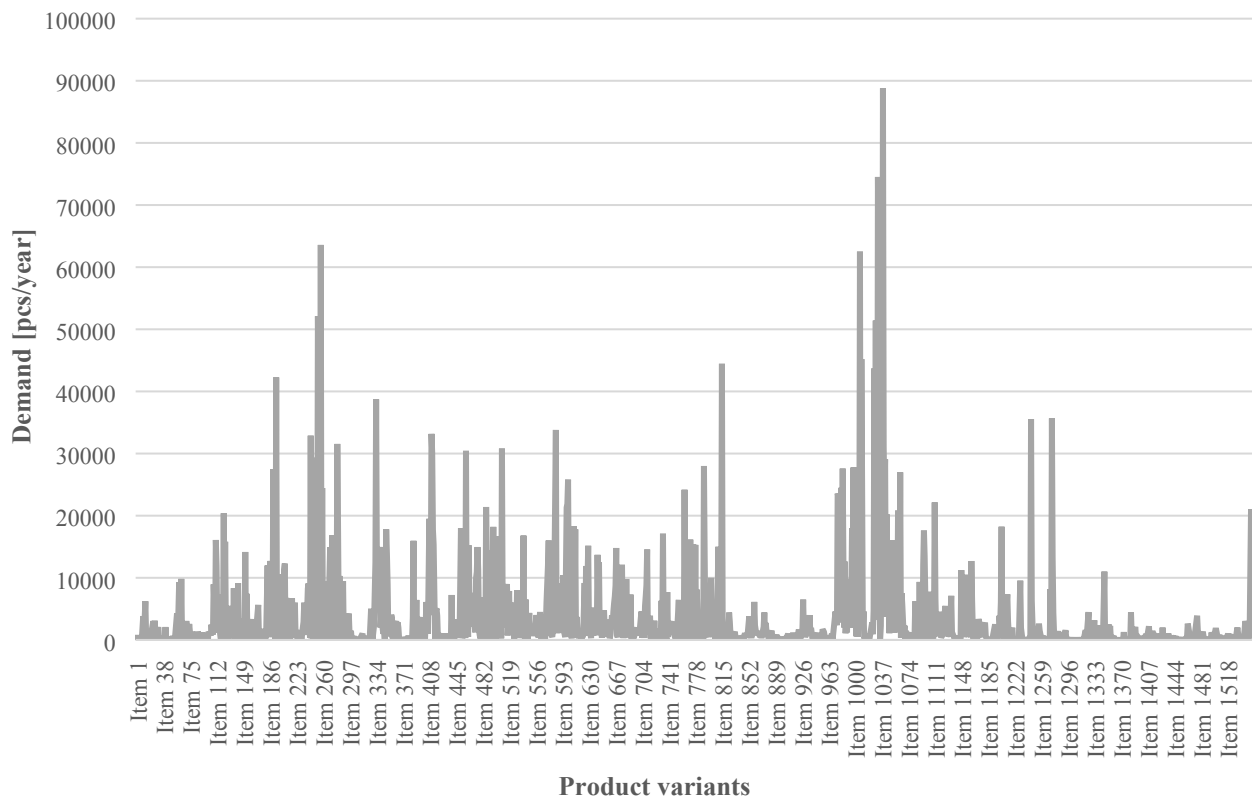


Figure 4. Annual production volume variation for the case company



**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 led, 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.





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.

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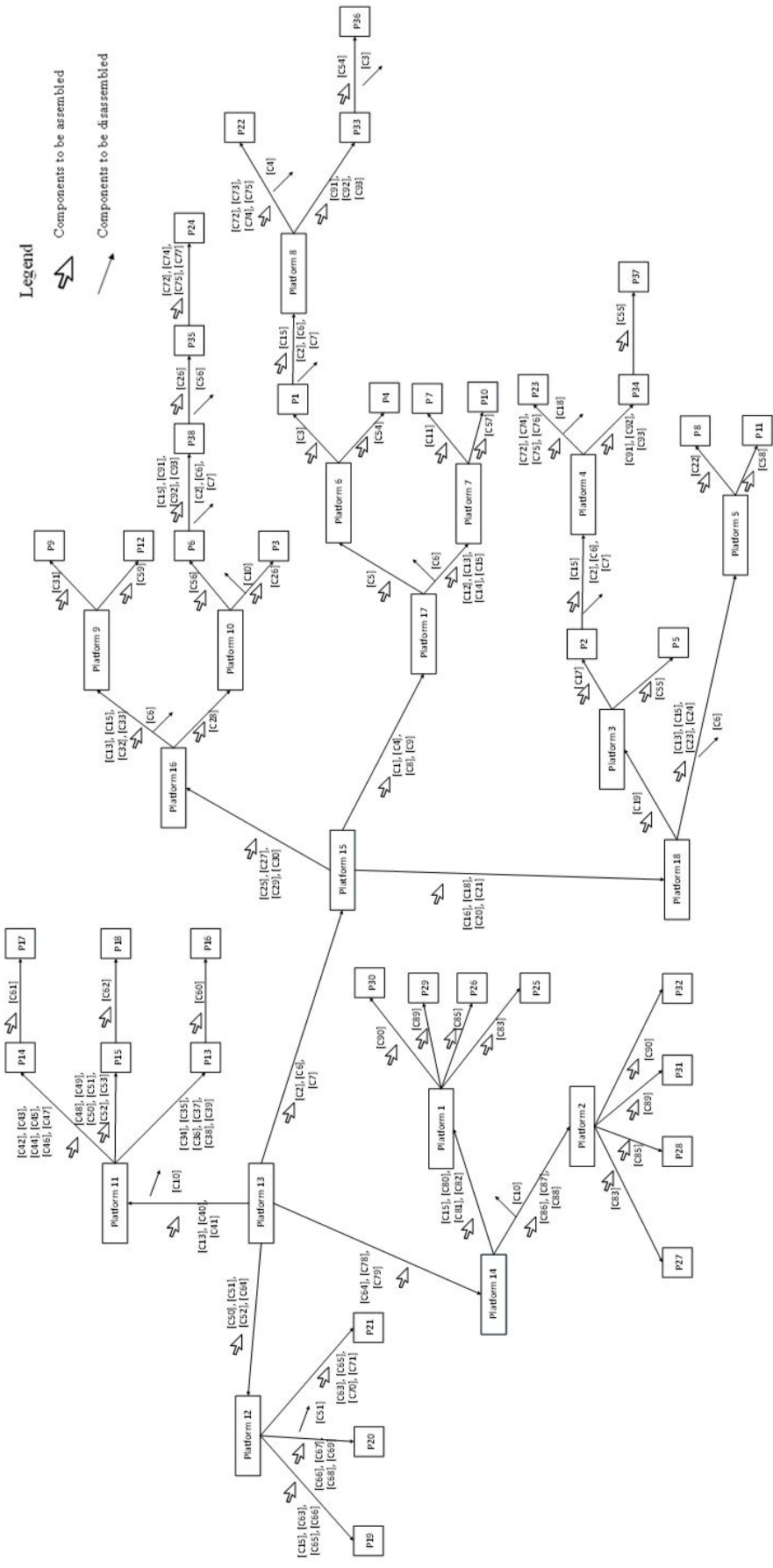


Figure 7. Phylogenetic network tree result for the family of plastic valves

**Table 1. Plastic valves platforms composition**

<i>Platform</i>	<i>Components</i>
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 ( $l = 1 \dots 7$ ) and for all levels  $l = 1, \dots, 6$  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):

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

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**

<i>Level</i>	<i>Formed platforms</i>	<i>N of components per platform</i>	<i>Platforms variety</i>	<i>Average components per platform</i>	<i>PRI</i>	<i>PCI</i>
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				
P14		9				
P15		9				
Plat12		5				
Plat1		8				
Plat2		6				
Plat9		11				
Plat10		9				
Plat6		9				
Level 5	Plat7	11	15	8.87	0.2	4.20
	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.

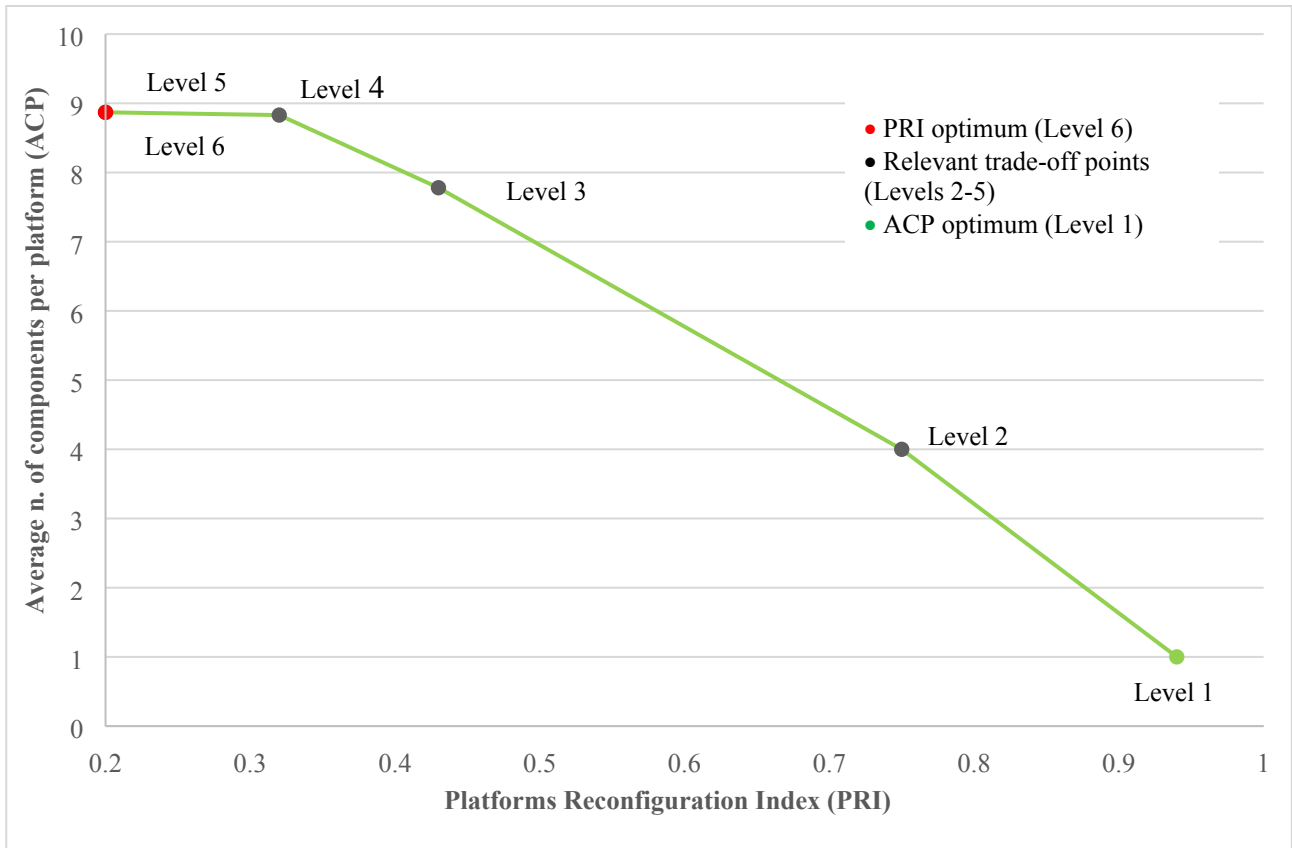


Figure 8. ACP vs. PRI trend

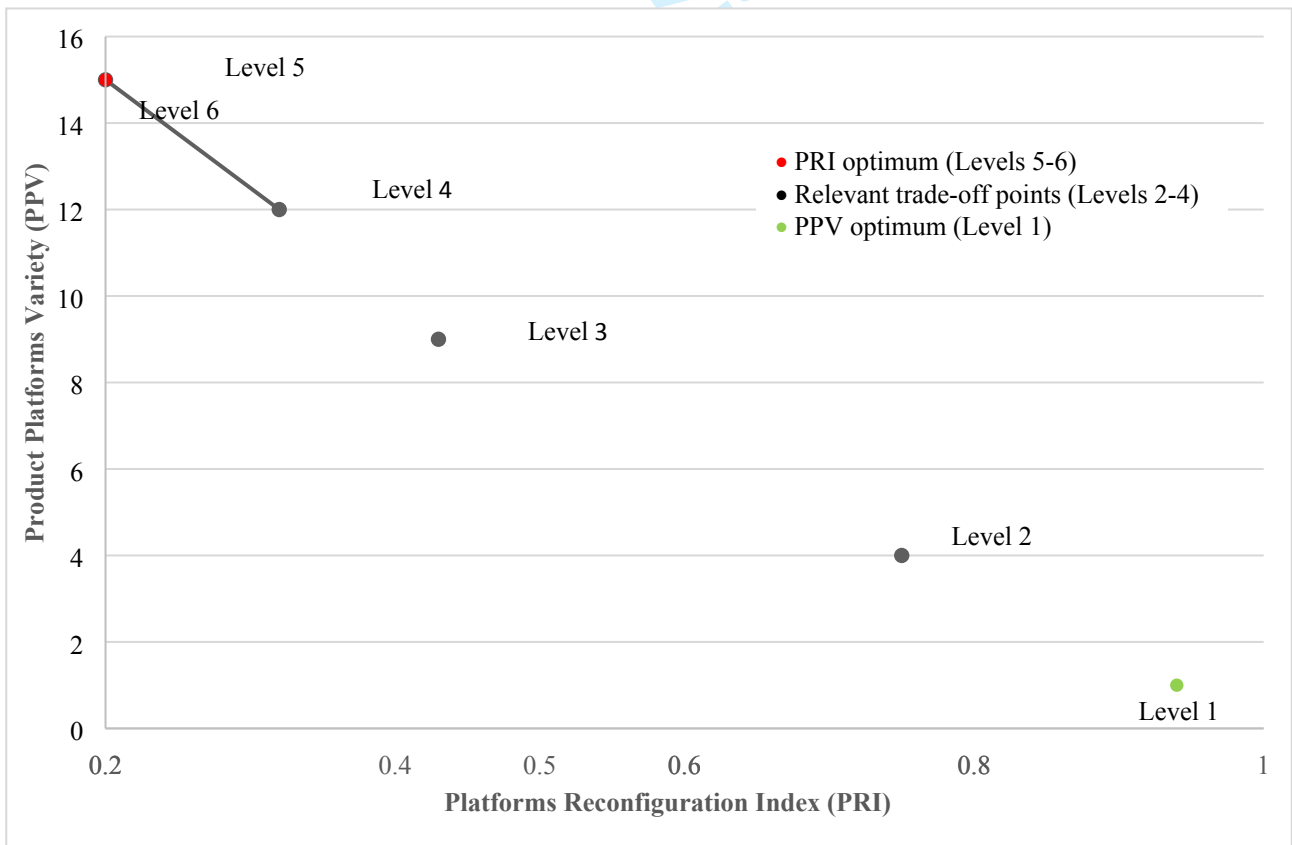


Figure 9. Platforms variety vs. PRI trend



#### 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.

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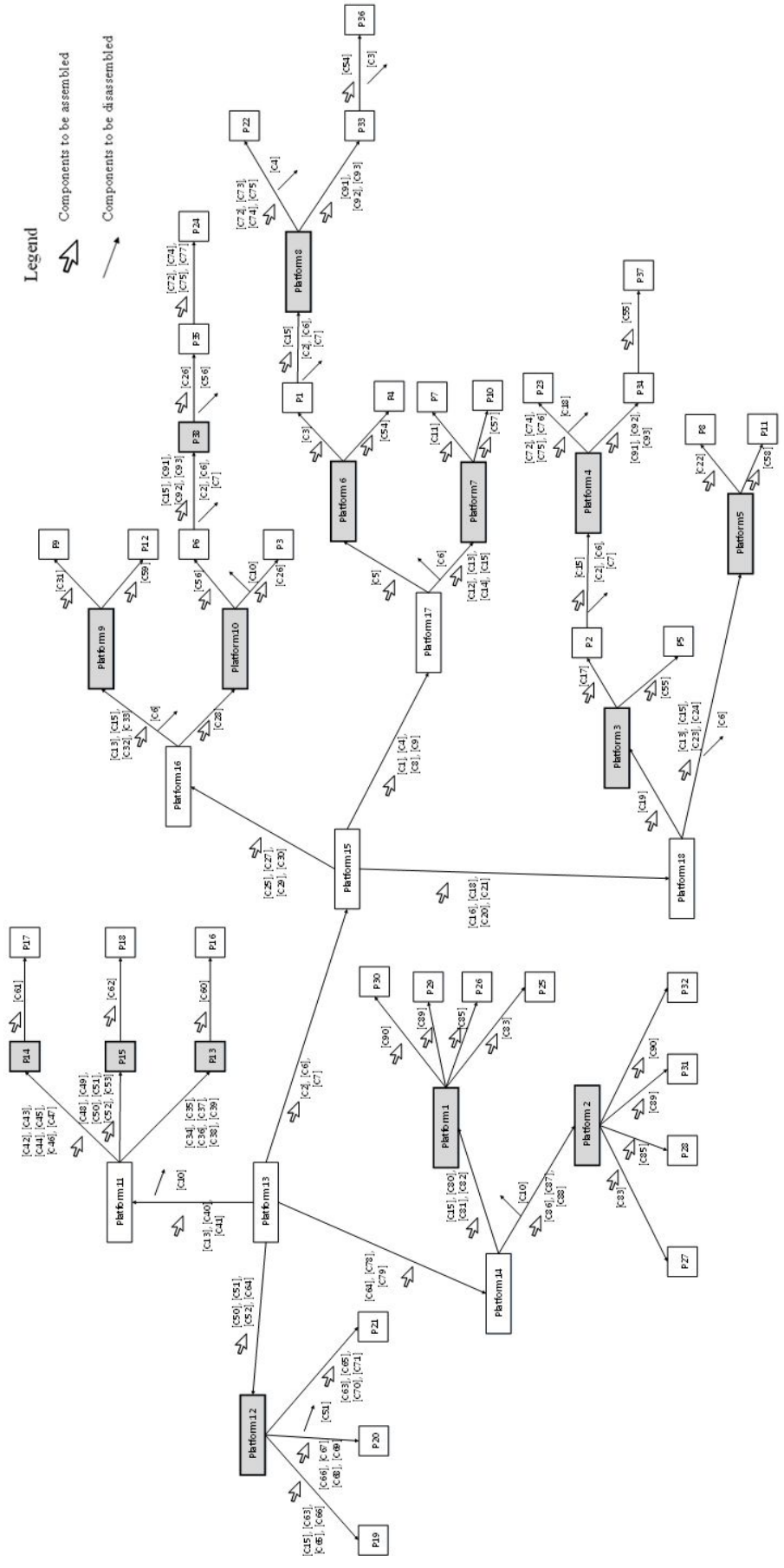


Figure 10. Final selection of product platforms

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

17  
18 The proposed DSS supports industrial companies in the transition towards the adoption of DPD by using  
19 product platforms providing detailed information about the platforms created in each level of reconfiguration  
20 together with the components involved in assembly and disassembly operations and the values of PRI and PCI  
21 indices, indicative of the cost of platform reconfiguration. Each level of the phylogenetic tree corresponds to  
22 a feasible DPD configuration and to a different trade-off between platform variety and platform reconfiguration  
23 effort which is an effective tool to guide industrial companies in the selection of the most suitable DPD  
24 configuration.

## 35 36 37 38 **5. Conclusions**

39  
40 Dynamic market demands and changing customers' requirements and regulations are responsible for products  
41 variety proliferation. The use of product platforms is an effective strategy to manage the increasing variety and  
42 to delay products differentiation. This paper proposes an innovative decision support system (DSS) for product  
43 platforms design and selection to best manage the trade-off between platforms variety and number of  
44 assembly/disassembly tasks to be performed to transform a product platform into a product variant through  
45 platforms reconfiguration and customization efforts. The Median-Joining Phylogenetic Networks (MJPN)  
46 algorithm is used in the design and planning phases to define the number and composition of different  
47 platforms using both assembly and disassembly to customize the platforms into product variants as needed  
48 based on orders. The MJPN methodology is a widely used approach in biology but is relatively new in the  
49 manufacturing field. After the platforms design, the phylogenetic tree is decomposed into multiple levels to  
50 assist with platforms selection. New metrics to measure platforms customization effort by considering the  
51 required assembly/disassembly tasks, i.e. Platforms Reconfiguration Index (PRI), and the ease of  
52 assembly/disassembly factors, i.e. Platforms Customization Index (PCI), have been developed. They represent  
53 an important new contribution to the application of products platforms customization for managing variety in  
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3 assembled products. In particular, such indices provide tools that support industrial companies in determining,  
4 for each product variant, whether it is better to adopt delay product differentiation (DPD) or assemble to order  
5 (ATO) strategy, and guide them in the selection of effective product platforms. A real case study of a large  
6 family of plastic valves is used to validate the proposed approach. The case studies found in literature involve  
7 small product families with limited number of products variants. In contrast, a family of thirty-eight (38)  
8 product variants is considered in this research. Each variant is composed of a combination of 9 to 14  
9 components, for a total of 93 components. Results show that the developed DSS efficiently supports companies  
10 in the design and selection of effective platforms, leading to a reduction of the variety of assembled and stocked  
11 products of about 60.5% and to significant production and inventory efficiencies and cost savings. At the same  
12 time, the company accepted an increase of assembly/disassembly effort required for platforms customization  
13 by about 20% and an increase of valves portfolio, which is more than offset by the reduction in inventory cost.  
14 Using the MJPN and the assembly/disassembly modular product platforms offer the possibility to produce  
15 different products using more than one platform, providing more flexibility in production planning. The  
16 introduction of product platforms also helps companies achieve a more flexible response to the introduction of  
17 new products mix as well as increased adaptability to changing market demands. Future research deals with  
18 the inclusion of the annual demand data of the different product variants to consider its effect on the platforms  
19 design.

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33  
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39  
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## Appendix 1

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

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

1									
2									
3		C13-C40-C41-C48-C49-C50-C51-							
4									
5	Plat 13 - P18	C52-C53-C62	10	C10	1	10	ATO	1	
6		C15-C50-C51-C52-C63-C64-C65-							
7									
8	Plat 13 - P19	C66	8	-	0	9	DPD	0.89	
9	Plat 13 - P20	C50-C52-C64-C66-C67-C68-C69	7	-	0	8	DPD	0.88	
10		C50-C51-C52-C63-C64-C65-C70-							
11									
12	Plat 13 - P21	C71	8	-	0	9	DPD	0.89	
13		C1-C3-C5-C8-C9-C15-C72-C74-							
14									
15	Plat 13 - P22	C75-C77	10	-	0	11	DPD	0.91	
16		C15-C16-C17-C19-C20-C21-C72-							
17									
18	Plat 13 - P23	C74-C75-C76	10	-	0	11	DPD	0.91	
19		C15-C25-C26-C27-C28-C29-C30-							
20									
21	Plat 13 - P24	C72-C74-C75-C77-C91-C92-C93	14	-	0	14	ATO	1	
22		C15-C64-C78-C79-C80-C81-C82-							
23									
24	Plat 13 - P25	C83	8	-	0	9	DPD	0.89	
25		C15-C64-C78-C79-C80-C81-C82-							
26									
27	Plat 13 - P26	C85	8	-	0	9	DPD	0.89	
28	Plat 13 - P27	C64-C78-C79-C83-C86-C87-C88	7	C10	1	7	ATO	1	
29	Plat 13 - P28	C64-C78-C79-C85-C86-C87-C88	7	C10	1	7	ATO	1	
30		C15-C64-C78-C79-C80-C81-C82-							
31									
32	Plat 13 - P29	C89	8	-	0	9	DPD	0.89	
33		C15-C64-C78-C79-C80-C81-C82-							
34									
35	Plat 13 - P30	C90	8	-	0	9	DPD	0.89	
36	Plat 13 - P31	C64-C78-C79-C86-C87-C88-C89	7	C10	1	7	ATO	1	
37	Plat 13 - P32	C64-C78-C79-C86-C87-C88-C90	7	C10	1	7	ATO	1	
38		C1-C3-C4-C5-C8-C9-C15-C91-							
39									
40	Plat 13 - P33	C92-C93	10	-	0	11	DPD	0.91	
41		C15-C16-C17-C18-C19-C20-C21-							
42									
43	Plat 13 - P34	C91-C92-C93	10	-	0	11	DPD	0.91	
44		C15-C25-C26-C27-C28-C29-C30-							
45									
46	Plat 13 - P35	C91-C92-C93	10	-	0	11	DPD	0.91	
47		C1-C4-C5-C8-C9-C15-C54-C91-							
48									
49	Plat 13 - P36	C92-C93	10	-	0	11	DPD	0.91	
50		C15-C16-C17-C18-C19-C20-C21-							
51									
52	Plat 13 - P37	C55-C91-C92-C93	11	-	0	11	ATO	1	
53		C15-C25-C27-C28-C29-C30-C56-							
54									
55	Plat 13 - P38	C91-C92-C93	10	-	0	11	DPD	0.91	
56									
57									
58									
59									
60	<b>Product platform variety</b>						<b>PRI</b>	<b>0.94</b>	<b>1</b>

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

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

1								
2								
3		C15-C50-C51-C52-C63-C64-						
4								
5	Plat 13 - P19	C65-C66	00	06	48	-	0	48
6		C50-C52-C64-C66-C67-C68-						
7								
8	Plat 13 - P20	C69	00	06	42	-	0	42
9		C50-C51-C52-C63-C64-C65-						
10								
11	Plat 13 - P21	C70-C71	00	06	48	-	0	48
12		C1-C3-C5-C8-C9-C15-C72-						
13								
14	Plat 13 - P22	C74-C75-C77	00	06	60	-	0	60
15		C15-C16-C17-C19-C20-C21-						
16								
17	Plat 13 - P23	C72-C74-C75-C76	00	06	60	-	0	60
18		C15-C25-C26-C27-C28-C29-						
19								
20		C30-C72-C74-C75-C77-C91-						
21	Plat 13 - P24	C92-C93	00	06	84	-	0	84
22		C15-C64-C78-C79-C80-C81-						
23								
24	Plat 13 - P25	C82-C83	00	06	48	-	0	48
25		C15-C64-C78-C79-C80-C81-						
26								
27	Plat 13 - P26	C82-C85	00	06	48	-	0	48
28		C64-C78-C79-C83-C86-C87-						
29								
30	Plat 13 - P27	C88	00	06	42	C10	6.12	48.12
31		C64-C78-C79-C85-C86-C87-						
32								
33	Plat 13 - P28	C88	00	06	42	C10	6.12	48.12
34		C15-C64-C78-C79-C80-C81-						
35								
36	Plat 13 - P29	C82-C89	00	06	48	-	0	48
37		C15-C64-C78-C79-C80-C81-						
38								
39	Plat 13 - P30	C82-C90	00	06	48	-	0	48
40		C64-C78-C79-C86-C87-C88-						
41								
42	Plat 13 - P31	C89	00	06	42	C10	6.12	48.12
43		C64-C78-C79-C86-C87-C88-						
44								
45	Plat 13 - P32	C90	00	06	42	C10	6.12	48.12
46		C1-C3-C4-C5-C8-C9-C15-						
47								
48	Plat 13 - P33	C91-C92-C93	00	06	60	-	0	60
49		C15-C16-C17-C18-C19-C20-						
50								
51	Plat 13 - P34	C21-C91-C92-C93	00	06	60	-	0	60
52		C15-C25-C26-C27-C28-C29-						
53								
54	Plat 13 - P35	C30-C91-C92-C93	00	06	60	-	0	60
55		C1-C4-C5-C8-C9-C15-C54-						
56								
57	Plat 13 - P36	C91-C92-C93	00	06	60	-	0	60
58		C15-C16-C17-C18-C19-C20-						
59								
60	Plat 13 - P37	C21-C55-C91-C92-C93	00	06	66	-	0	66
		C15-C25-C27-C28-C29-C30-						
	Plat 13 - P38	C56-C91-C92-C93	00	06	60	-	0	60

*PCI*      *21.97*

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

For Peer Review Only