Process Planning for Mass Customization

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Abstract: Process planning connects product designs and the production of the designed products. It determines the production cost, quality and production cycle time. Usually one process plan is built and fixed for a unique product design before the production. However in mass customization, the possible number of unique products can be astronomical in order to satisfy diversified individual customer needs. The complexity of the product variety will be transferred to the process planning. In addition, in response to the diversified customer needs, modern manufacturing systems introduce more flexible resources for producing the diverse products within short times while maintaining good quality. One of the consequences of increasing use of flexible resources is the explosive number of potential process plan alternatives for each unique product. The compounding effects of product variety and process variety can result in a chaotic manufacturing and negative economical consequences. It is imperative to develop a new approach of process planning that not only can handle the great complexity derived from the product variety and the flexible resources, but also can capture the process plan alternatives for each unique product in order to fully subjugate the flexibility of the manufacturing systems for achieving mass customization. This paper develops such an approach that dynamically generates the process plan with alternatives for each unique product on demand. It is built based on the rationalization of product variety and process variety as well as their relationships. A case study is presented to illustrate the approach.
1 Introduction

1.1 Process planning

Process planning is an important manufacturing function in enterprises that selects the manufacturing processes and specifies the operation parameters to convert a part from its initial form to a final form (Luttervelt, 2003). It is the communication channel between product designers and the manufacturing engineers. The inputs of the process planning function are the data of resources on the shop floor and the design data in the form of blueprint, CAD models or detailed product feature description (see Figure 1). Process planning makes decisions of selecting the proper operations, defining the precedence of the operations, assigning the resources and facilities such as machines, fixtures, tools etc. and specifying the operation parameters. These decisions are then transformed into a set of detailed working instructions, which are documented and named as a “process plan”, i.e. the output of the process planning function (Zhang, 1994).

![Figure 1. Overview of the process planning function](image)

Approaches to process planning can be classified into two categories: manual process planning by process planners and computer aided process planning (CAPP). Figure 2 shows the hierarchical classification tree (Zhang and Alting, 1994).

![Figure 2. Hierarchical classification tree of process planning](image)

Traditional approach. In this approach, process planners need to examine the information of a part design from a blueprint, identify similar parts from their memory or codebooks, and then manually retrieve process plans for these similar parts. After that, they need to modify and adapt the old ones to a new one that meets the special requirements of the new part design.
**Workbook approach.** It is an alternative of the traditional approach and is more efficient. Process planners construct a workbook containing a menu of pre-stored operations for given types of features. To create a process plan for a new part, process planners will manually retrieve the operations from the menu according to the features of the new part and then link the operations with certain sequence into the required process plan. One of the advantages for workbook approach is the flexibility—a well-trained process planner can produce a large number of process plan alternatives for a simple part.

**Variant approach.** The variant approach for CAPP is comparable to workbook approach but in a systematic manner with the help of computing technologies. Parts are grouped into families according to their similarity in terms of manufacturing methodologies by group technology (GT). One standard process plan is built and stored for each family. When the process plan for a new part is requested, the new part will be first classified into a part family by coding. The standard process plan of the part family is then retrieved by the computer and revised by the process planner for the new part. A representative CAPP system following variant approach is MIPLAN (Houtzeel, 1976).

**Generative approach.** It is of the highest level of automation and complexity in CAPP. In this approach, process plans are generated by the means of decision logic, formulas, technology algorithms and geometry-based data processing etc. The capabilities of available resources and manufacturability rules are stored in the computer system. With such a system process plans can be generated without the involvement of process planners (Halevi, 1999; Zhang, 1994). Some representative generative process planning systems are APPAS (Zhang, 1994), GARI (Descotte and Latombe, 1985), IAI-CAPP (Chang and Chang, 2000).

**Semi-generative approach.** It is an interim approach that entails interaction between a computer and process planners. It employs the computing technology to retrieve the details of the operations such as measurements, materials, and tolerances etc but leave the difficult feature interpretation to the human being, i.e. process planners. With the interactive input of part features, operation selections and operation precedence assignment from process planners, the computer will generate a process plan based on pre-defined algorithms and formulas.

Up to now, due to the complexity of the process planning, especially on the product feature recognition and completely modeling the capabilities of manufacturing resources, CAPP systems are still elusive. As pointed by Elmaraghy (1993), around 85% of process plans in industry are still generated manually.

### 1.2 Challenges of process planning for mass customization

Mass customization aims at best satisfying individual customer needs with near mass production efficiency. To satisfy diversified customer needs, the number of possible product offerings can easily be of millions (Zhang and Tseng, 2002). In addition, in order to produce the diversified products within short lead times while maintaining good quality, modern manufacturing systems introduce more flexible resources such as CNC machines, tool magazines and cross-trained workers. One of the consequences of increasing use of flexible resources is the explosive number of potential process plan alternatives for each unique product. The compounding effects of product and process proliferation make it economically impractical if not impossible to manually build and maintain the astronomical number of process plans with alternatives for each unique product.
However, the new challenges of process planning for mass customization are not addressed by the existing CAPP approaches either. The astronomical number of process plans makes it economically impractical to apply the variant approach and semi-generative approach since both approaches need the process planner’s involvement for each process plan. The generative approach sounds a good idea, but still, there exists the problem of feature recognition and resource capabilities modeling. Hence, a new approach is requested for the process planning in mass customization. The new approach should (1) avoid the great efforts of process planners due to the great number of distinct products; (2) consider the process plan alternatives to fully explore the flexibility of the manufacturing systems; and (3) capture the resources changes and reflect the availabilities of the resources on the shop floor.

This paper is to address the challenges of process planning in mass customization. A dynamic process planning approach is proposed based on the rationalization of product and process variety as well as their relationships. The commonalities of the process plans can be utilized to achieve the economies of scale by sharing the tools, fixtures, machine setups etc. Process plan alternatives are captured so that the flexibility of manufacturing systems can be fully subjugated for achieving mass customization. An industrial case study is presented to illustrate the proposed approach.

In the next section the background of the illustrative case is introduced. Section 3 presents the rationalization and representation of product and process variety as well as their relationships. Section 4 proposes the dynamic process plan generation approach. Section 5 concludes the paper.

2 Case description

In the case an industrial product, called high-pressure washer, is analyzed. The basic function of the high-pressure washer is to perform cleaning in and around the house, e.g. moss-covered or dirty surfaces such as facades, patios, paths, walls, swimming pools, garden furniture and tools, and to wash vehicles. According to the marketing research, customers are interested in customizing many attributes of the high-pressure washer, such as size of the washer, material of the coating for the handle-stick, power of the engine varying from 2 to 3.5 KW, color and material of the body, and so on. The number of total possible distinct products counts up to the order of $10^9$. This paper will take the example of the high-pressure washer to illustrate how to handle the challenges of process planning discussed in the previous section.

3 Rationalization of product variety, process variety and their relationships

3.1 Product variety and Generic Bills-of-Materials (GBOM)

A view is held in this paper that the diversified product offerings in mass customization can be classified into product families by the similarity in the product structures. The product structure of a product is the way in which a product is built up from purchased parts and/or semi-finished products (which in turn consist of other semi-finished parts and/or purchased parts) (van Veen, 1992). Members of a product family, i.e. product variants, share a similar product structure and differentiate by different values of customized attributes. In the high-pressure washer case, all the distinct products with
different customized attributes belong to the same product family. The diversity among all the product variants of a product family is referred to product variety in this paper.

Product variety originates from diverse customer needs and it is an important source of process variety in manufacturing systems. Thus it is important to rationalize the product variety in order to systematically handle the process variety in process planning. To characterize the product variety, Generic Bills-of-Material (GBOM) (first introduced by Hegge and Wortmann, 1991) is applied. In essence, a GBOM represents a family of products that share a similar BOM structure (Hegge and Wortmann, 1991). A generic item is introduced to represent a family of similar items that differ from each other by different values of certain attributes (also called variety parameters). A generic item can be the end product, a subassembly, an intermediate part or a purchased part. The relationships between the generic items are defined in the GBOM construction to assure the validity of the product family design (for details see Zhang et al., 2003). Each product variant can be specified in the form of "item-attribute-value" to accurately capture the uniqueness of this particular product.

The graphical GBOM of the high-pressure washer product family is shown in Figure 3. The detailed variety parameters and their values of each item and the relationships between them are tabulated in Appendix 1.

![Figure 3. Graphical GBOM of high-pressure washer product family (partial)](image_url)

3.2 Process Variety and Master Process

A manufacturing process refers to the transfer process from raw materials and purchased parts into the end product through certain routing that contains the corresponding resources and facilities such as machines, tools and fixtures etc. As we know, the details of the processes are documented in the process plans. In this paper the process variety is defined as the diversity of the manufacturing processes that produce the product variants within the product family. It is represented by the differences in the process plans in terms of the involved operation definitions and the sequences among the operations, i.e. different routings.
Master Process was proposed to represent a family of process plans that share the rough process structure, namely, the high level process routings and corresponding resources (Zhang et al., 2003). For example, all possible process plans to manufacture a family of office chairs are represented by the Master Process of the office chair family. The processes start from the fabrication of the chair stands, armrests and seats and it ends with the final assembly. Along the processes we need general resources such as injection moulding machines and assembly workstations. In order to provide a view of different levels, a hierarchical structure is employed as shown in Figure 4 (where \( a_j \)'s represent different possible sequence alternatives of the defined operations). An operation module is a set of operations with defined sequences.

\[
\begin{align*}
\text{Seq0:} & \quad a_1: O_1 \rightarrow O_2 \rightarrow O_{sw} \\
\text{Seq3:} & \quad a_1: O_{sw} \rightarrow O_{f2} \rightarrow O_{ksw} \\
& \quad a_2: O_{sw} \rightarrow O_{f3} \rightarrow O_{ksw}
\end{align*}
\]

**Legend**
- **Generic operation (module)**
- **Common operation (module)**
- **Operation i**
- **Operation module i**

**Figure 4. Hierarchical structure of Master Process**

In Master Process order a generic operation (represented by \( O_i \), \( i \) is the index of the operation) is introduced to represent a wide variety of similar operations with a single data structure. Usually it represents a type of operations. For example, metal cutting is a generic operation that can cut steel and aluminum with different cutters by two different cutting machines. The modeling of the generic operation captures six set of information, namely required materials, output items, machines/workstations, tools/fixtures, setups and operation parameters (Zhang et al., 2003). Operation parameters are divided into operation variety parameters and common operation parameters. Only operation variety parameters will have the relations with the product variety. Suitability rule is defined to specify the following properties of each operation according to different required materials and different requirements for the output item: (1) applicability constraints of each resource (workstation or machine), (2) selection of fixtures and tools, (3) setup requirements and (4) operation variety parameter settings. A generic operation will degenerate into a common operation if there is no variety in the selection of machines/workstations and tools/fixtures, the setting of operation variety parameters and setups for the production of all product variants.

To facilitate the relationships development between product and process variety, a process differentiation driver (PDD) is defined as the process variety descriptor. A PDD
can be a generic operation, a generic operation module or a set of sequence alternatives.

The Master Process of the high-pressure washer product family is partially detailed in the Appendixes 2 and 3. To save the space, the setting of common operation parameters is omitted.

### 3.3 Developing relationships between product and process variety knowledge

The relationships between the product and process variety are defined as cause and effect relations between the changes of the product design and the corresponding changes in the manufacturing process. In order to study the relationships in an orderly manner, a Matching Matrix is introduced. It is a tool to tabulate both product and process variety in one table so that the relationships between them can be studied.

#### 3.3.1 Matching Matrix

The Matching Matrix is constructed as shown in Table 1. The variety parameters of the generic item, say, $M_j$, are listed on the horizontal axis, while the PDDs of the operation module in the Master Process, say, $O_{im}$, are arrayed on the vertical axis. The horizontal axis also lists the optional structural relationship, which is treated as the same as the variety parameters attached to the child item. Product designers and manufacturing engineers can fill in the table either row-by-row or column-by-column.

The content of the relationships are classified into four types. “R” refers to that different values of the corresponding variety parameter of the generic item will result in different routings; similarly, “WS/M/F/T” means the variety correspondence between the workstation/machine/fixture/tool selection and the variety parameter of the generic item; “S” means the variety correspondence between the setups and the variety parameter of the generic item; and “P” means the variety correspondence between the operation variety parameters and the product variety parameter. The detailed description of relationships for each cell is stored in a database behind. During the relationships development, “X” marks can be put in the corresponding cell as long as either of the conditions hold: (1) PDD is an operation module; and (2) the variety parameter is inherited by or a function of at least one of the variety parameters of lower level child items.

<table>
<thead>
<tr>
<th>Product variety by $M_j$</th>
<th>$VP_{j1}$</th>
<th>$VP_{j2}$</th>
<th>$VP_{j3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PDD_{1}$ (Seq.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$PDD_{2}$ ($O_{i1}$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$PDD_{3}$ ($O_{i3m}$)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Matching Matrix for the mapping between variety parameters (VPs) of generic item $M_j$ and PDDs of operation module $O_{im}$
Due to the complexity in both product variety and process variety knowledge, the mapping between them is in fact a recursive process. In order to maintain an order for easy relationships developing and retrieving and reduce the redundancy in the mapping process as well, a mapping cycle is introduced.

### 3.3.2 Mapping cycle

A mapping cycle is defined as the mapping to study the corresponding process changes due to different instantiation of the variety parameters (including the optional structural relationship) of ONE generic item in the GBOM of the product family. For example, the generic item M2, i.e. the “Hose Rewinder” in the GBOM structure of the high-pressure washer product family (see Appendix 1), has three variety parameters: “Size”, “Color”, and “Material”. The mapping cycle for the “Hose Rewinder” depicts the relationships between these three variety parameters and the process varieties. For example, what is the process variety if the “Size” of the “Hose Rewinder” is changed between “mini” and “normal”? The mapping cycle for the “Hose Rewinder” provides answers to these questions. The first matching matrix is constructed as shown in Figure 5(a). As we can see, because the related PDD, i.e. “O2m=Hose Rewinder Mfg”, is an operation module, new matching matrixes have to be generated to resolve the “X” marks by further going down along the Master Process structure. The new matching matrix is shown in Figure 5(b), which is between the variety parameters of the generic item M2, the “Hose Rewinder”, and the PDDs in the decomposed sub-process of “O2m=Hose Rewinder Mfg”. In this specific example, all the three “X” marks can be resolved. In reality it may move steps down along the Master Process structure in order to resolve all the “X” marks. The detailed relationships represented by the abbreviations are stored in a database behind. For example, “R” in the cross (seq2, VP3) of Figure 5(b) refers to that “if the raw material of the Hose Rewinder is PP (a type of plastics), the first routing is taken (see Appendix 4); otherwise, the raw material is stainless steel and the second routing should be selected”. The mapping cycle reveals that the change of the “Size” from “mini” to “normal” will not result in any changes in the sequence of the operation, but will change the selection of machines, tools, and setups in the two operations, namely “O21=Hose Rewinder Injection Moulding” and “O22=Metal Wheel Mfg”. The links between the “X” marks and their resolutions are expressed as the dotted arrows shown in Figure 5.
In the mapping cycle of a generic item, all the relationships related to the generic item can be developed except that the variety parameter of the generic item is inherited by or a function of some child items, in other words, when the condition (2) holds. So whenever some "X" marks are not resolved within the mapping cycle, they must be resolved in the mapping cycles of the corresponding child items. The linkage between this type of "X" mark and its resolution is also built and stored for the convenience of relationships retrieving.

The mapping process won’t end until the mapping cycles for all generic items in the GBOM are conducted and no “X” mark is not resolved.

4 Dynamic process plan generation

The GBOM and the Master Process rationalize the product variety and process variety respectively. The correlations between the product variety and process variety are represented by the defined relationships. Given the specification of any product variant, the corresponding process plan with alternatives can be automatically generated on demand. There are three major steps to generate a process plan:

Step 1. Transfer the specification of the requested product variant into the “item-attribute-value” form and check the design validity of the product variant. This is accomplished based on the GBOM of the product family.

Step 2. Instantiate the generic operations as specific operation instances with defined details and specify the operation sequences based on the specification of the requested product variant and the developed relationships between product variety and process variety.

Step 3. Link all the common operations and operation instances with specified sequences into the process plan for the requested product variant.
Take an example of the high-pressure washer product family. Assume a product variant is requested by a customer. Through step 1 the specification of the requested washer is transformed into the "item-attribute-value" form as listed in Table 2.

<table>
<thead>
<tr>
<th>Item Name</th>
<th>Symbol</th>
<th>Type</th>
<th>Inherited VPs</th>
<th>Other VPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pressure Washer</td>
<td>M0</td>
<td>End product</td>
<td>None</td>
<td>Size normal</td>
</tr>
<tr>
<td>Drawing Bar</td>
<td>M1</td>
<td>Sub-assembly</td>
<td>None</td>
<td>Size normal</td>
</tr>
<tr>
<td>Handle</td>
<td>M11</td>
<td>M1.Size</td>
<td>Material PP</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Coating without leather</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Color yellow</td>
<td></td>
</tr>
<tr>
<td>Handle-stick</td>
<td>M12</td>
<td>Intermediate part</td>
<td>None</td>
<td>Color natural</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Material PP</td>
<td></td>
</tr>
<tr>
<td>Hose Rewinder</td>
<td>M2</td>
<td>Intermediate part</td>
<td>None</td>
<td>Size normal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Color yellow</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Material PP</td>
<td></td>
</tr>
<tr>
<td>Closed Body</td>
<td>M3</td>
<td>Sub-assembly</td>
<td>M0.Size</td>
<td>None None</td>
</tr>
</tbody>
</table>

Table 2. Transformed specification of a requested product variant (partial)

Step 2 is to specify the PDDs according to the required product specification based on the defined relationships between product and process variety. For example, the “Hose Rewinder” item (M2) is specified as “normal” size, “yellow” color, and “PP” material. According to the defined relationships shown in Figure 5, PDDs are instantiated as follows:

“Seq2” is correlated with the “Material” of the “Hose Rewinder”. Since the material is specified as “PP”, the first alternative of the sequence is chosen (see Appendix 4), namely, only operation “O21=Hose Rewinder Injection Moulding” is involved;

“O21” is correlated with the variety parameter “Size” and “Color”. For this specific example, the "normal" size can be manufactured by the two injection moulding machines (see Appendix 4), so there exist alternatives. Inserting tools are not required since they are only for “mini” size; the "yellow" color determines that deep clean is required if previous production is for a dark color hose rewinder.

In summary, the generic operation module “O2m=Hose Rewinder Mfg” is instantiated as "O*2m=O*21" with details as follows, where symbol “*” means that it is an instance of the generic operation or operation module:

O*21= instance of generic operation “Hose Rewinder Injection Moulding”

- Workstation: none
- Machine: Injection Moulding machine M1 (KM650-3500C), M2 (KM650-5700C)
- Fixture: none
- Tool: Mould for normal size hose rewinder, cutting knife
- Setup: (1) If previous material color is dark, then need deep cleaning , Else, normal cleaning; (2) Replace mould if the previous production is not for the Hose Rewinder; (3) Load the material
- Operation parameters: (1) Clamping force=3000KN; (2) Injection Pressure=9 (KN/cm^2); (3) After Pressure=6.0 (KN/cm^2); (4) Nozzle Temperature=200
Centigrade degree; (5) Flange Temperature = 40 Centigrade degree; (6) Mould Temperature = 30 Centigrade degree; (7) Injection time = 2.5 s; (8) Cooling time = 35 s

It happens that the two alternatives in the process plan employ two similar machines in the same generic operation. Sometimes the alternatives go through different operations (e.g. milling and grinding) by utilizing different machines. Consequently the details of the process alternatives will be specified separately.

After all the generic operations are instantiated and the sequence alternatives are specified according to the specification of the requested product variant, step 3 links all the common operations and generic operation instances with specified sequences following the Master Process structure. The final process plan for the product variant is generated then, as shown in Figure 6. To save the space the details of the operations are not listed in this paper.

Figure 6. Generated process plan for the requested product variant
5 Conclusion

To achieve the goal of mass customization, not only the number of product offerings becomes astronomical, which leads to the great complexity in process planning to build and maintain the astronomical number of process plans, but also the process plan alternatives brought by the flexible resources makes the process planning even more complicated. Meanwhile the changes of resources and facilities on the shop floor will invalidate some of the predefined process plans. To address the above problems, this paper presents an approach to dynamically generate the process plans on demand. In essence, it is a generative approach but integrated with the advantages of product families, namely the product variety and process variety can be rationalized. Resource changes can be easily handled by indicating the availability of the resources. For example, if any machine breaks down, it will be marked as unavailable and will not be included in the newly generated process plans. In addition, the process plan alternatives are captured in the process planning so that the flexibility of the manufacturing systems can be fully explored to produce diversified product offerings within short lead times while maintaining good quality. The third advantage of the dynamic process plan generation approach is that the commonalities of the process plans for different product variants can be easily derived. Economies of scale can be achieved in the production through sharing the tools, fixtures, machine setups and expertise etc.

The premise of this paper is that good engineering practices in product design require a well articulated product family with commonality defined in the physical designs of their product offerings, no matter how wide span their product variety is. Likewise, there are similarities existing among the variety of the manufacturing processes that can be deployed for the products. These premises enable the rationalization of the product and process variety as well as their relationships, represented by the GBOM, the Master Process and rules in the Matching Matrix respectively (Zhang et al., 2003). The dynamic process plan generation approach is built on the basis of this rationalization. The approach has been illustrated and validated with an industrial product. The results have shown its effectiveness and efficiency in process planning for mass customization.

References


G. Halevi, 1999, Restructuring Manufacturing Processes, St. Lucie Press


Appendixes

Appendix 1 (a). Partial detailed information for the GBOM of high-pressure washer product family: generic items and parent-child relationships
<table>
<thead>
<tr>
<th>Item Name</th>
<th>Symbol</th>
<th>Type</th>
<th>Quantity/quantity/quantity/</th>
<th>SR-1</th>
<th>Inherited VPs</th>
<th>Other VPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pressure Washer</td>
<td>M0</td>
<td>End product</td>
<td>1</td>
<td>None</td>
<td>None</td>
<td>Size mini, normal</td>
</tr>
<tr>
<td>Drawing Bar</td>
<td>M1</td>
<td>Sub-assembly</td>
<td>1</td>
<td>1</td>
<td>None</td>
<td>Size mini, normal</td>
</tr>
<tr>
<td>Handle</td>
<td>M11</td>
<td></td>
<td></td>
<td></td>
<td>M1.Size</td>
<td>Material PP(transparent, half transparent, opaque), wood, aluminium (Al)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Coating with/without leather</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Color green, yellow, black, white, red, natural</td>
</tr>
<tr>
<td>Handle-stick</td>
<td>M12</td>
<td>Intermediate part</td>
<td>2</td>
<td>1</td>
<td>None</td>
<td>Material PP(transparent, half transparent, opaque), wood, aluminium (Al)</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Color green, yellow, black, white, red, natural</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Material PP(transparent, half transparent, opaque), wood, aluminium (Al)</td>
</tr>
<tr>
<td>Hose Rewinder</td>
<td>M2</td>
<td>Intermediate part</td>
<td>1</td>
<td>1</td>
<td>None</td>
<td>Size mini, normal</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Color green, yellow, black, white, red, natural</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Material PP(transparent, half transparent, opaque), stainless steel</td>
</tr>
<tr>
<td>Closed Body</td>
<td>M3</td>
<td>Sub-assembly</td>
<td>1</td>
<td>1</td>
<td>M0.Size</td>
<td>None</td>
</tr>
</tbody>
</table>

Appendix 1 (b). Detailed information for the GBOM of high-pressure washer product family: non-parent-child relationships

<table>
<thead>
<tr>
<th>Constituent Items</th>
<th>Inter-constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawing Bar; Hose Rewinder</td>
<td>Drawing Bar. Size = Hose Rewinder.Size</td>
</tr>
<tr>
<td>Engine, Cylinder-head</td>
<td>If Engine.Power ={2, 2.5KW}, THEN Cylinder-head. Input Motor Power = type I; o.w. Cylinder-head. Input Motor Power = type II</td>
</tr>
</tbody>
</table>

Appendix 2. Decomposition of O0m for high-pressure washer product family
## Appendix 3. Decomposition of “Hose Rewinder Mfg” (O2m)

<table>
<thead>
<tr>
<th>Manufacturing capability</th>
<th>Resources &amp; Facilities</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Symbol</td>
<td>Common/PDD</td>
</tr>
<tr>
<td>Closed Body Mfg</td>
<td>O1m</td>
<td>PDD</td>
</tr>
<tr>
<td>Hose Rewinder Mfg</td>
<td>O2m</td>
<td>PDD</td>
</tr>
<tr>
<td>Brush Mfg</td>
<td>O3m</td>
<td>PDD</td>
</tr>
<tr>
<td>Drawing Bar Mfg</td>
<td>O4m</td>
<td>PDD</td>
</tr>
<tr>
<td>Washer Assembling</td>
<td>O5</td>
<td>Common</td>
</tr>
</tbody>
</table>

\[
O_{1w} \rightarrow O_{2w} \rightarrow O_{3w} \rightarrow O_{4w} \rightarrow O_{5w} 
\]

<table>
<thead>
<tr>
<th>Sequence 2 (Seq2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ a_1 : O_{11} ]</td>
</tr>
<tr>
<td>[ a_2 : O_{12} \rightarrow O_{11} ]</td>
</tr>
</tbody>
</table>