PRODUCT FAMILY MANUFACTURING BASED ON DYNAMIC CLASSIFICATION

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According to requirements of the market a great number of small companies are forced to offer a wide variety of products and to frequently respond to the market with customized solutions. At the same time, the fast delivery of products is often key to winning orders. Recent developments in Information Technology have made product family manufacturing available for small companies. It is made possible by applying a class of software tools called product configurators which can be integrated with Enterprise Resource Planning (ERP) systems. This paper presents production management based on dynamic classification. High-variety production like mass customization is facing the challenge of effective variety management, which needs to deal with numerous variants of both product and process in order to accommodate diverse customer requirements. In high-variety production, in spite of applying modern management techniques, setup time still plays an important part in the production cycle time. The problem is not single change over time, but is in the quantity of changeovers required. This observation inspired the author to prepare a method of setup time reduction through the appropriate arrangement of tasks in the operational production plan. The appropriate arrangement of tasks means considering the similarity of parts from the point of view of operation carried out. The similarity of parts facilitates setup time reduction, which translates into smaller lot sizes, reduced in-process inventories, shorter lead time and higher throughput. The presented method is one of the elements of a computer aided management system for high-variety production. The method was validated in the conditions of best practice for unit and small batch production.

Keywords
dynamic classification, operational production plan, group technology, unit and small batch production, high-variety production, product family.

Introduction

The design and operation of current logistical and manufacturing systems is a very complex task. The designer of such systems has to evaluate many variants of manufacturing systems influenced by sets of endogenous and exogenous factors [1–3]. It is a widely accepted practice to utilize product diversity and process variation to develop product families in which a set of similar variants share $M$ differentiates within common structures. The primary source of competitive advantage for manufacturing companies in many industries was related to price. Therefore, all manufacturing strategies were driven by attempts to reduce the cost of the product. Technological advances, in manufacturing as well as in information, have provided the impetus for changes in many paradigms, including customer expectations. Customers have become more demanding and want products that can meet their specific individual requirements [2–4]. Thus customization is turning out to be essential to maintaining competitive advantage in many industries. Producing customized products at a low cost, which seemingly is a paradox, is the purpose of many enterprises [5]. This main purpose, which is considered as fulfilling customer...
needs, results in production by unit and small batch process. The production cycle consists of, among others: the processing time and setup time. Despite using modern management techniques (e.g. SMED Single Minute Exchange of Die Technique) in the conditions of unit production in small and medium enterprises (SME), total setup time is significant.

For high-variety production, the cumulative amount of the setup time derives from the number of changeovers. In the examined companies of the SMEs sector the relationship between setup time and processing time is still high and ranges over a few to several per cent of the processing time.

The above research inspired the author to prepare a method of setup time process based on the similarity of the products. In order to do this a classifier of a new kind was introduced – the classifier works at the level of process in the operation production plan. The objective of the classifier is to aggregate processes into organizationally similar groups. It allows production tasks to be completed inside groups: in sequences, without changeovers or by significantly shortening the setup process. The above classification is based on the features of tasks having influence on changeover times and optimization of task arrangement.

Focusing on the work bottleneck and improving it is the essence of this approach. This approach corresponds with the assumptions of the theory of constraints (TOC) [6–7]. Increasing the productivity of the bottleneck follows from the dynamic classification of tasks in the operational production plan.

The paper is structured as follows. First, the studied problem is shortly described. Then, an example to illustrate the problem is presented. The main part of the article consists of assumptions of dynamic classification and clustering. Next is the description of the main solutions the company envisaged in formalizing its product knowledge. The changes in the operational management processes and in their performances are also discussed. The article concludes with some summary remarks.

**Problem background**

Manufacturing based classification began to evolve in the 1940s. It is based on the idea that products do not have to look the same to be similar. Although they may appear to be different, they can be manufactured in the same way. It becomes possible to develop a classification system that groups products according to their manufacturing characteristics [8–9]. When analyzing literature it is possible to find many methods of recognizing product similarities. The most important are: classification and grouping. Classification is a statistical sciences term and can be defined as a procedure in which individual items are placed into groups based on quantitative information on one or more characteristics inherent to the items (referred to as traits, variables, characters, etc.) and based on a training set of previously labeled items [10–11].

Machine-part grouping problems were also considered in many publications [12–14]. This issue is referred to as “part family & machine cell formation”, “machine part grouping” or “group technology manufacturing”. The problem arises when dividing a group of machines into subsets and assigning operations to these subsets in order to optimize a production organization quality criterion. In [15] the attempts to solve this problem with clustering methods were outlined.

Although the problem generally concerned the improvement of industrial engineering, the purpose of the optimization was situated elsewhere. This criterion reflects the “density” of operation within the established machine groups and the “sparseness” of operations outside of these groups. Additional aspects that complicate the formulation of the solution to the general problem are: timing, costs, sequencing of operations, the possibility of duplication and the cost of machines, as well as various limitations on the groups.

The concepts of high-variety manufacturing are described in literature by [16–17], and others. Some researches were focused on the optimization of data preparation and the modeling of product structure (e.g. [18–20]). They linked the product configuration process to the process through which the customer’s needs are translated into the information needed for tendering and manufacturing (typically product cost, bill of materials (BOM), production cycle, etc.). The attention management literature recently devoted to the issue of product configuration is also related to the importance of software applications. Advances have been incorporated in a new class of software products supporting the product configuration process called product configurators. The concept of Mass Customization (MC) producing customized goods for a mass market, has received considerable attention in research literature [21–22]. The fundamental types of operation for mass customization were given in [23–25]. A risk and limit of mass customization is known as “mass confusion”, which is a metaphor for the burden of the consumer resulting from attractive but probably overloaded options [16, 26]. More and more often, small and medium-sized enterprises (SME) are using software
to increase the functionality of their products and offerings. Variability management by software is becoming an interesting topic for SME with expanding portfolios and increasingly complex product structures.

To utilize commonality, underlying product diversity and process variation, it has been a widely accepted practice to develop product families, in which a set of similar variants share common product and process structures and variety differentiates within these common structures [27]. Conception of product configurators is designed for product families. The product family is composed of possible configuration solutions \( P = \{ P_1, P_2, \ldots, P_n \} \) with AND relation. Each solution \( P_i \) \( \forall i \in [1, N] \) could be derived through adjusting the configurable modules, \( M = \{ M_1, M_2, \ldots, M_K \} \). Each configurable module \( M_i \) \( \forall i \in [1, K] \) may possess several available module instances \( M_i^k = \{ CA_{k1}, CA_{k2}, \ldots, CA_{kL} \} \) with OR relation, out of which, one and only one instance can be selected for a certain configuration solution. While customers always purchase products according to product performance, each module instance is characterized with the corresponding product attributes \( A = \{ a_{kq} \} \), and their values \( D = \{ d_{kqr} \} \) where \( d_{kqr} \) indicates the \( r \)th value of the \( q \)th attribute associated with the \( k \)th module.

Figure 1 illustrates the decision framework of product family design and development along the entire spectrum of product realization according to the concept of design domains. Based on such a view, product family design and development encompasses five consecutive domains, namely the: customer, functional, physical, process and logistics domains. Product family decision-making involves a series of “what how” mappings between these domains. The customer domain is characterized by a set of customer needs (CNs) representing the segmentation of markets that have demand for product families and triggering downstream product family design mappings in a cascading manner. The CNs are first translated into functional requirements (FRs) in the functional domain, in which designers take into account engineering concerns and elaborate these requirements based on available product technologies [28].

The mapping between the customer and functional domains constitutes the front-end issues associated with developing product families. Such a product family definition task is always carried out within an existing product portfolio and manifests itself through those common practices of order configuration and sales force automation. Product family design solutions are generated in the physical domain by mapping FRs to design parameters (DPs) based on the shared product platform. This stage involves typical decisions regarding product family design and configuration. At the front-end, the product portfolio articulates detailed achievement of customer satisfaction in the customer domain in the form of specifications of functionality in the functional domain. On the other hand, the main focus of platform-based product family design is the technical feasibility of DPs in terms of fulfilling the specified functionality [28].

![Fig. 1. High-variety production issues.](image-url)
The back-end issues associated with product families involve the process and logistics domains, which are characterized by process variables (PVs) and logistics variables (LVs), respectively. The mapping from DPs to PVs entails the process design task, which must generate manufacturing and production planning within existing process capabilities and utilize repetitions in tooling, setup, equipment, routings, etc. Corresponding to a product platform, production processes can be organized as a process platform in the form of standard routings, thus facilitating production configuration for diverse product family design solutions [27]. Since then main concern in the process domain is manufacturability and cost commitment, process design is the de facto enabler of mass production efficiency [28].

Problem formulation

Effective company management requires the right quality data which can be provided by an integrated information system. Therefore, a large number of SMEs have decided to introduce an ERP class system although they have recognized that the introduction process is difficult and expensive. However, an alternative solution cannot be easily found [2–3]. In the majority of companies the introduced ERP systems were not fulfilling expectations in the area of operational production control. Companies need efficient tools within the decision-making process which can work in an “on line” mode.

An efficient production system realizes “make to order” manufacturing of configurable products. Due to the fact that the system resources are not wholly used, it is possible to accept additional orders. Prior to commencing the realization of these orders one should answer the following questions:

1. Do the resources possessed make it possible to complete the orders on time without exceeding the limitations?
2. If the demand for resources exceeds availability, is it possible to increase the availability of resources (improve the bottleneck)?

In other words, one should find an answer to the following questions:

How to distribute production orders among alternative routes? What resources should be allocated to jobs to complete the orders on time and without exceeding constraints?

Such a formulation of the problem serves to emphasize its decision-making nature. So, a feasible variant of a given work order schedule, following both the customer’s requirements and the manufacturing system capabilities, is sought.

To solve this basic problem, different computer methods are used. Some concern virtual enterprises [1] or Digital Factories (DF) [29]. The author used the method of dynamic classification. This method can be developed as a potential source of supply for Digital Factory.

Solution method

The basic element of the above method is defining the features of the product family which have an impact on the changeover times. The above features are defined from the perspective of workstations and process production operations.

For example, for the varnishing line, the major influence on the changeover time is the colour of the varnish. Regardless of shape (which does have an influence on the processing time), if there are elements painted the same colour in the same set of tasks then the line will not need to be rearmed. Using the standard construction classifier in this case – where the subject of classification is an element and not the operation – can have unwanted effects. The groups would be created for elements of the same kind.

When designing the production process we do not know in what sequence the elements will be made and as a result we assign the full setup time in the base Product Data Management (PDM) or ERP class software. If we arrange the tasks properly we can lower the setup times to a greater extent. Setup times cannot be lowered to zero but let us assume that we are able to assess the lowering of setup times for the remaining elements which constitute such a prepared group.

Assignment into the groups is not limited. The basic limitation is the required production time. The group cannot consist of too many elements because when performing the tasks for the whole group we perform them faster than is needed and we absorb the resources. Although we shorten work consumption, we lengthen the unit production time. We are searching for an optimum in a multi-criterion optimization of the cycle length, work consumption and production costs. In fact, the process of classification itself has a dynamic character which depends on organizational conditions. Creating such groups in a manual way would not be useful either, which is why it requires information technology (IT) support. This method could even be identified as a semi-automatic one.

Assignment to the similar elements group is based on the criterion of similarity at the level of the production process operation. The criteria are rather static but the given element – and in fact the task of
the production process operation, can dynamically belong:
• to different groups in different operations of the production process,
• due to organizational limitations, to different groups fulfilling even the same statistical similarity criteria.
Taking into account the above assumptions, a heuristic method of arranging was created and verified by tests in real conditions.

**Illustrative Example**

The example in this paper is the customization and production of product families for roller shutters manufactured in SME. Roller shutters are one example of family products. For roller shutters, the parameters for configuration are shown on Table 1. A crucial role in waste-free manufacturing of roller shutters is played by the rollforming line.

It’s possible to produce, in one process, a complete roller shutter curtain. The rollforming line is equipped with tooling suitable to produce the foamed roller shutter profiles in different sizes. The process consists of foaming, punching and cutting to length operations. The line is designed for high density or low density foamed profiles. It is also possible to add a stacking bench to make packages or cut to length curtains complete with side caps. Depending on the type of profile the line can reach a productivity of approximately 50-60 m/min. Unfortunately, the changeover time of the line is 2 hours. Until now, shutter manufacturing was based on profiles supplied in 6m sections. The profile was then cut to length according to individual customer requirements.

<table>
<thead>
<tr>
<th>Node</th>
<th>Parameter</th>
<th>Possible values of parameters</th>
<th>Amount of values</th>
<th>Comments</th>
<th>Group type</th>
<th>Kind/ Influenace</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PA System P1</td>
<td>{39, 41, 45, 52}</td>
<td>4</td>
<td>System determines the width of the profile.</td>
<td>PAN/SKR</td>
<td>D +++</td>
</tr>
<tr>
<td>2</td>
<td>Width dimension P2</td>
<td>From 300 to 3800.</td>
<td>about 3500</td>
<td>Maximum roller width depends on the PA system. For example, for PA = 39 is equal to 2800 and for PA = 41 is equal to 3800.</td>
<td>PAN/SKR</td>
<td>D ++</td>
</tr>
<tr>
<td>3</td>
<td>Colour of profile P7</td>
<td>{brown, dark brown, blue,...}</td>
<td>About 12 or 1000</td>
<td>Parameter values depend on the supplier of profiles.</td>
<td>PAN</td>
<td>D +++</td>
</tr>
<tr>
<td>4</td>
<td>Colour of box P8</td>
<td>{brown, dark brown, blue,...}, full range of RAL</td>
<td>About 12 or 1000</td>
<td>Parameter values depend on the supplier of profiles. It is also possible to paint profiles in any RAL colour</td>
<td>SKR P8</td>
<td>D +++</td>
</tr>
<tr>
<td>5</td>
<td>Kind of box P9</td>
<td>{130,150,180,...}</td>
<td>4</td>
<td>Parameter values depend on the supplier of boxes.</td>
<td>SKR</td>
<td>D +++</td>
</tr>
<tr>
<td>X</td>
<td>P20</td>
<td>&lt;0;10&gt;</td>
<td>∞</td>
<td>Priority of superior order. Parameters from P20 to P23 are limitations of assignment to the group. P 20 is suggesting not to arrange elements into groups with divergent priorities of orders.</td>
<td>PAN/SKR</td>
<td>O _ _</td>
</tr>
<tr>
<td>X</td>
<td>P21</td>
<td>&lt;0;168&gt;</td>
<td>∞</td>
<td>Date of delivery. The due date scheduled in the plan will be a basic parameter dividing organizationally similar groups.</td>
<td>PAN/SKR</td>
<td>O _ _</td>
</tr>
<tr>
<td>X</td>
<td>P22</td>
<td>{T,F}</td>
<td>2</td>
<td>Release the operation (the previous operation was performed and material is available)</td>
<td>PAN/SKR</td>
<td>O T _</td>
</tr>
<tr>
<td>X</td>
<td>P23</td>
<td>&lt;0;10&gt;</td>
<td>∞</td>
<td>Delaying task in the production plan</td>
<td>PAN/SKR</td>
<td>O _</td>
</tr>
</tbody>
</table>
The next stages of the process are the curtain assembly, the box cutting and the final assembly of other materials and components. Manufacturing from 6 m profile sections did not allow for waste-free production. It’s possible only on the rollforming line with cutting to length according to individual customer requirements. The above line is computerized numerical controlled (CNC) and the controlling data are transmitted automatically by the manufacturing execution system (MES). The process can be implemented by alternative routes (Fig. 2).

**Defining parameters of tasks having influence on changeovers time**

In this step, position groups were divided into homogenous types by those parameters which have an influence on changeover time. For each element of the set of machines \( M_X = \{m_1, m_2, \ldots, m_n\} \) a choice was made of those parameters which have an influence on changeover times and they were assigned to \( m_1 : \{p_{11}, p_{12}, \ldots, p_{1k}\} \), \( m_2 : \{p_{21}, p_{22}, \ldots, p_{2l}\} \), \ldots, \( m_n : \{p_{n1}, p_{n2}, \ldots, p_{nm}\} \). The assignment of parameters will not be sufficient; the influence of the above parameters on reducing changeover time also needs to be taken into account. The above parameters will constitute the basic criterion in the classification and the creation of groups. The criterion itself can assume static values but the assignment of the given task to the group will take a dynamic character dependent on the organizational features or resource constraints.

Apart from the choice of parameters, limitations should also be introduced in the division of the tasks into groups. The major limitation in the assignment of tasks to groups will be the time criterion. Tasks with a distant planned performance deadline can be rejected from a group. In the above way a dynamic classifier is created according to task features at the level of the production process operation which causes, depending on the classification moment, the same element to be classified differently. In one case it can be assigned to a group and in the other it can be rejected. The above features have positive, negative or neutral influence. They can be of the design (D), technological (T) or organizational (O) type. In order to define the influence of features on
the tasks arrangement process, a matrix of assignment to organizationally similar groups was created for each of these types. In order to do that for each of these groups the dependence on features as well as the kind of influence for this type of connection was defined. Influence means assignment to the organizational group and the method of calculation of changeover time.

**Dynamic groups forming**

Two types of groups were formed for roller shutters: boxes and curtains (Fig. 3). A B2B (business to business) data system was used for the definition of the set of tasks for assignment purposes. After performing the scheduling function in the set of tasks, the planned terms were defined and recorded on the list. Tasks were narrowed to groups of machines having bottlenecks (PAN – groups for curtains and SKR – groups for boxes).

The most interesting groups were formed by tasks in the first week on the list. In conditions of changeable operational production plans, the consideration of the subsequent weeks is pointless. In order to increase the productivity of calculations, the task list has been narrowed to the first week. Classification into organizationally similar groups at the level of production process operations is a key classification for the whole method.

There are several possible classification scenarios. For classification into organizationally similar groups the author applied an algorithm shown on Fig. 4. After calculating the parameters for the two types of groups, the author applied pattern classifications. The problem of pattern classification can be stated in a formula as follows: given training data \( \{(x_1, y_1), \ldots, (x_n, y_n)\} \) produce a classifier \( h: X \to Y \) that maps any object \( x \in X \) to its true classification label \( y \in Y \). Sets \( O_1, O_2, \ldots, O_m \) where \( O_i = \{I_{d_1}, I_{d_2}, \ldots, I_{d_z}\} \) has a separate character and \( O_i \subseteq O, \bigcup_{i=1}^{m} O_i = O \) for \( \forall i, k \in I_d \) condition \( O_i \cap O_k = \emptyset \) is satisfied.

![Fig. 3. Dynamic groups forming.](image-url)
The assignment of elements’ set $I_d$ to the set of groups $O_k$ is a function dependent on parameters $P$: \( \{I_d \in O_k: F(p)\} \). Set was divided into as many classes as there were labels $y_i \in \{1, 2, ..., g\}$ created, where the label is a unique value of a parameter having a strong influence on setup time. In the case of the roller shutter two kinds of group appeared.

One of them is defined by the forming of curtains and the other by the forming of boxes. For groups of curtains, the strong influence on setup time has $P_1$ and $P_7$ parameters (see Table 1). The number of created groups is equal to the unique and not empty value of a parameter $P_1$ and $P_7$. For groups of boxes, the strong influence on setup time has $P_1$, $P_8$ and $P_9$ parameters (see Table 1). The number of created groups is equal to the unique and not empty value of a parameter $P_1$, $P_8$ and $P_9$. In Fig. 3 groups of curtains and boxes are shown with the decision making process of manufacturing.

**Subgroups forming**

Subgroups were formed on the basis of cluster analysis. Clustering algorithms generally follow hierarchical or partition approaches. Hierarchical cluster methods produce a hierarchy of clusters from small clusters of very similar items to large clusters that include more dissimilar items. Hierarchical methods usually produce a graphical output known as a dendrogram or tree that shows this hierarchical clustering structure. Some hierarchical methods are divi-
sive, that is progressively divide the one large cluster compressing all of the data into two smaller clusters and repeat this process until all clusters have been divided [11]. Other hierarchical methods are agglomerative and work in the opposite direction by first finding the clusters of the most similar items and progressively adding less similar items until all items have been included into a single large cluster [11].

Partition clustering algorithms require a large number of computations of distance or similarity measures amongst data records and cluster centers, which can be very time consuming for large data bases. Moreover, partition clustering algorithms generally require the number of clusters as an input parameter. However, the number of clusters is usually an unknown priori, so the algorithm must be executed many times, each for a different number of clusters. The algorithm uses a validation index to define the optimal number of clusters. In the case of forming organizationally similar groups calculating the amount of groups is possible.

At this stage of classification a subdivision of groups based on subgroups is shown:

The sets \( O_{ix} \) were formed: \( \forall i \in \{1, 2, ..., m\}, O_i = \{O_{i1}, O_{i2}, ..., O_{ip}\} \) where \( O_{ix} = \{Id_{x1}, Id_{x2}, ..., Id_{xz}\} \). Groups have separate characters: \( O_{ix} \subseteq O_i \), \( O_i \subseteq O \), and \( \cup O_{ix} = O_i \), \( \bigcup O_i = O \), where \( \forall i, k \in Id \) conditions are satisfied: \( O_i \cap O_k = \emptyset, \forall i, k \in IdO_{ix} \cap O_{kx} \).

The assignment of the elements’ set \( Id_i \) to the set of groups \( O_{ix1} \) is a function dependent on parameters \( P: \{Id_{ix} \in O_{ix}: F(p)\} \). At this stage of classification organizational parameters: P20- P23 played an important role.

Clustering aims to find useful groups of objects (clusters), where usefulness is defined by the goals of the data analysis.

The decision about the amount of clusters is undertaken based on the following two assumptions: the machine works in a one shift system and the working day consists of 8 hours. The parameter P21 is a feature which strongly influences the formation of the groups.

Final grouping

The first two stages consisted of creating groups and subgroups. Classification took place according to the similarity of the technological parameters P1–P19. The grouping (e.g. in the case of the curtain of the roller cutter – the index of cartesian set \( P1 \times P7 \)) was strongly influenced by preserving organizational limitations (P20–P23). The next phase of forming groups was the final grouping.

The final grouping took place based on the results of the first two phases. Additional conditions for the moving of elements between subgroups were taken into consideration. It wasn’t possible to carry out the above task in step 2 because of the organizational nature of the parameters which limited grouping. In this phase, we moved tasks within neighboring subgroups, verifying the results of the grouping with additional limitations. All groups where these subgroups appeared at the front of the queues were then analyzed, i.e. a decision was made as to which tasks should be completed first.

This is not necessary for all workstations applying the 3rd stage. Furthermore, a lack of underlying data in the classical structure of an ERP package can cause additional problems for the classification. Often in order to complete this stage the dataset for parameters must be extended in order for the above analysis to apply. As a result of a calculation of the above phase even entire clusters can disappear. Subgroups can be assimilated by preceding index subgroups.

Conclusions

The method which has been introduced in this paper gives more scope to the profitability of IT projects in the future. This approach seems to be an excellent tool for a decision making model for SMEs. In consequence, this method can be an alternative for expensive and difficult to implement scheduling methods. Constraint-based scheduling with dynamic classification are efficient tools for solving real-life scheduling problem in an “on line” mode.

Managing product families consisting of a large set of product variants as configurable products requires defining a configuration model. The concepts and modeling guidelines for them were validated with success in SME for roller shutters. Information system support is necessary for modeling products, particularly for a configurator available on the Internet for B2B partners. Modeling sets new requirements for the designer. In addition to having a good understanding of the product, a designer should be familiar with object oriented modeling. The main benefit there would be improving communication within the product development team and to other departments in the company, e.g. sales. The benefits also include the use of additional functions provided by the knowledge database, structure and the related design constraints during the product development.
References


