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Quick Response Manufacturing for High Mix, Low Volume, High Complexity Manufacturers

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Abstract
The market of consumer goods requires nowadays quick response to customer needs. As a consequence, this is transferred to the time restrictions that the semi-finished product manufacturer must meet. Therefore the cost of manufacturing cannot determine how production processes are designed, and the main evaluation function of manufacturing processes is the response time to customers' orders. One of the ideas for implementing this idea is the QRM (Quick Response Manufacturing) production organization system. The purpose of the research undertaken by the authors was to develop an innovative solution in the field of production structure, allowing for the implementation of the QRM concept in a Contract Manufacturer, which realizes its tasks according to engineering-to-order (ETO) system in conditions defined as High Mix, Low Volume, High Complexity. The object of the research was to select appropriate methods for grouping products assuming that certain operations will be carried out in traditional but well-organized technological and/or linear cells. The research was carried out in one of the largest producers of sheet metal components in Europe. Pre-completed groupings for data obtained from the company had indicated that – among the classical methods – the best results had been given by the following methods: King's Algorithm (otherwise called: Binary Ordering, Rank Order Clustering), k-means, and Kohonen's neural networks. The results of the tests and preliminary simulations based on the data from the company proved that the implementation of the QRM concept does not have to be associated with the absolute formation of multi-purpose cells. It turned out that the effect of reducing the response time to customer needs can be obtained by using hybrid structures that combine solutions characteristic of cellular systems with traditional systems such as a technological, linear, or mixed structure. However, this requires the application of technological solutions with the highest level of organization.

Keywords
Quick Response Manufacturing, engineering-to-order, contract manufacturer, cellular systems.

Introduction

Contemporary markets of consumer goods require a quick response to customers' needs. Consequently, semi-finished product manufacturers must meet time restrictions. This challenge for manufacturers has led to lead-time-oriented production, which became a competing alternative for the canon concepts that select production processes based on the cost of manufacturing.

It is widely recognized today that the time response to demand is the main criterion for evaluating manufacturing processes. The cost of manufacturing is less important, though necessary to take into account. As a result, manufacturing methods using IT technologies and the concept of time compression have become more and more popular. One can mention JIT, KANBAN, Lean Manufacturing, Paired-Cell Overlapping Loops of Cards with Authorization – POLCA and QRM. The latter approach combines the elements of the remaining concepts (Shah, 2003) and is the most effective method of shortening product lead time (Suri, 2010). The principles of JIT and KANBAN very

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quickly became part of the canon of production management, while the concepts of Lean Manufacturing and QRM needed refinement.

QRM, as a method of modeling and designing manufacturing processes, is rooted in the concept of Time-Based Competition (TBC) pioneered by Japanese enterprises in the 1980s and described for the first time in the United States (Stalk, 1988). QRM, in contrary to TBC, focuses solely on manufacturing processes (Godinho Filho and Veloso Saes, 2013). It takes advantage of the dynamic of a manufacturing system to reorganize a company so that it can quickly respond to customers' needs (creation of manufacturing capacity reserves, reduction of production batches) (Suri, 1998):

- provides management with clear instructions on how to implement product lead time reduction (QRM mindset),
- provides ten specific rules for the reengineering of existing processes to adapt them to quick response manufacturing (change of manufacturing structure),
- offers a completely new concept of material and control planning (in contrary to MRPII/ERP),
- provides new performance measures (QRM number) and finally,
- instructs how to maintain QRM effects over a long period (awareness of QRM rules among all people related to the manufacturing process, starting from workers working in the production shop to cooperators in the entire supply chain).

QRM was initially treated as an idea for running a business, not requiring special research, but only convincing managers of its effectiveness. Very quickly, however, it turned out that the effective implementation of this concept requires solving many research and scientific problems (Dos Santos and Deutsch, 2010), among which the most important are:

- cellular layout namely a physical arrangement where the machines are grouped into manufacturing cells to produce families of parts or products,
- improvement of hybrid production control system specially designed for QRM cells combining features of MRP and Kanban,
- forming Quick Response Office Cell (Q-ROC) – the QRM recommends the use of cells also in the office's operations, not only in the shop floor,
- concurrent engineering as a method of designing and developing products, in which the different stages run simultaneously, rather than consecutively,
- design for manufacturability – method of design for ease of manufacturing of the collection of parts that will form the product after assembly.

The literature on the effects of QRM is mainly concerned with producers that supply a relatively small number of different products directly to the market. The problem of introducing QRM in the case of Contract Manufacturer (CM) (manufacturer that contracts with a firm for components or products) is still unsolved, especially when dealing with a wide portfolio of diverse, complex short-run products (High Mix, Low Volume, High Complexity – HMLVHC). There is a significant group of producers among Contract Manufacturers that manufacture custom-made products outside the defined production program. This kind of manufacturing pattern is called Engineering to Order or Engineer to Order (ETO). It is characterized by the fact that procedures related to the technical preparation of production (engineering activities) need to be added to product lead time; and also by the fact that upon receipt of a customer order, the order engineering requirements and specifications are not known in detail. The problem of implementing Lean Manufacturing concepts, including QRM, in HMLVHC enterprises, has been the subject of numerous studies (Dos Santos and Deutsch, 2010). Their results indicate that in the case of HMLVHC the problem of cellular layout formation is particularly difficult to solve. Unfortunately, the literature view has shown that research related to the adaptation of the QRM concept to the needs of MTO (Make to Order) and the ETO focus on production control problems. This is evidenced by the comprehensive review of the research presented in the work (Fernandes and Do Carmo-Silva, 2006), confirmed by the latest publications (Büyüközkan et al., 2015; Onyeocha et al., 2015).

In our opinion, the key unsolved problem is the development of an appropriate production structure that enables the implementation of the QRM concept. QRM, to a large extent, uses the concept of cellular manufacturing to reduce preparation-completion times and to reduce the flow time through processing lines. This, in turn, reduces interoperation stocks and shortens the time of delivery of products to a market (Wemmerlöv and Hyer, 1989). Reduction of preparation-completion times is achieved mainly by using manufacturing cells for groups of products, whereas the shortening of the flow time is achieved by manufacturing in small production batches.

The QRM method, by definition, is based on creating machine cells (QRM cells) based on a focused target market segment (FTMS). The FTMS, according to QRM, denotes the segment for which shortening the delivery time of products to a customer is the most profitable for enterprises (Suri, 2010). Determining FTMS for CM and HMLVHC is extremely difficult, if at all possible. It is a serious research challenge to use this approach in enterprises with a technologically diversified portfolio of executed orders requiring the implementation of technical production preparation processes for each product separately.

The purpose of the research undertaken by employees of the Faculty of Management in cooperation with ADDIT Ltd. company, as part of a project co-financed from European funds and AGH own resources, was to develop an innovative solution for a production structure, allowing for the implementation of QRM in a Contract Manufacturer type enterprise that carries out its ETO tasks under the conditions of High Mix, Low Volume, High Complexity.

The motivation to undertake the research presented in this paper were the problems of meeting the guaranteed deadlines for the realization of low-volume and high-complexity orders in ADDIT Ltd. Preliminary analysis of these problems indicated that they can not be solved in the existing technological production structure of the company, and the use of classical subject structure is impossible given the high variability of orders. Our research was based on data from the above-mentioned company but concerns many companies operating under the model that will be presented in Section 4.

Moreover, after an in-depth review of the literature, the authors did not find solutions to such problems. It was therefore decided that a cellular system was necessary, but the implementation of this task required appropriate research.

QRM problem for enterprises with a diverse, variable portfolio of MTO orders

One of the basic ways to implement the concept of quick response manufacturing (QRM) is the re-engineering of manufacturing processes based on the concept of group technology that consists in the creation of group technology cells (the so-called cellular systems) in place of the traditional technological structure.

The design of cellular manufacturing systems is a decision problem that can be formalized as follows (Selim et al., 1998):

- starting from the given set of:
  - products,
  - technological requirements for their production,
  - the demand for these products in a certain period,
  - and available resources (machines, equipment, etc.)
- realize the following tasks:
  - form families of products based on the similarity of their manufacturing requirements,
  - group machines into machine cells,
  - allocate products to the cells.

As reported in the literature, these activities don't have to be carried out in the order presented above; they even don't have to be carried out sequentially.

Depending on the needs, three strategies of realizing this task can be distinguished (Domański and Hadaś, 2008):

1) first, families of products are formed and then machines are grouped according to the needs of the formed families of products (Part Family Identification – PFI),
2) first, machine cells (groups of machines) are created based on the similarity of products flow; then products are allocated to the machine cells (Machine Groups Identification – MGI),
3) product families and machine cells are formed in parallel (Part Families / Machine Grouping – PF/MG).

The specificity of enterprises operating in accordance with the ETO model encourages us to adopt the PF/MG strategy. In the case of complex production processes, a wide range of products, and uncertainty of product parameters this process is very complicated, and universal methods for satisfactory solutions have not been developed yet.

The problem of designing and improving this type of production process, which consists in defining the production structure and production management procedures that will correspond to a difficult to predict order structure, has not been solved so far.

Enterprises operating in accordance with the Engineer to Order (ETO) principle cannot formulate rules for the creation of production processes a priori, as the exact portfolio of manufactured products is not known.

In order to implement the concept of QRM manufacturing, we must design production processes so that they correspond to the concept of machine cells that guarantee the rapid implementation of production orders in the presence of data uncertainty.

A highly diversified potential production program makes it difficult to group products so that they can be manufactured in group technology cells.

An additional difficulty is the occurrence of "soft" restrictions that do not allow the grouping of products into one cell and are difficult to capture in mathematical models (dimensions, mutually exclusive materials, health and safety, human resources and their qualifications, etc.).

The assumption was made that the formation of group technology cells will not be treated as an absolute imperative. The specificity of technological processes may lead to the creation of hybrid structures that combine solutions characteristic for cellular systems with traditional systems such as a technological, linear, or mixed structure. This required adaptation of known techniques and methods for forming cells to the specifics of Contract Manufacturer performing their ETO tasks under the conditions of High Mix, Low Volume, and High Complexity.

Methods of creating production structures for needs of QRM in conditions of variability of order portfolio

The process of developing the pattern of production processes compatible with the QRM concept uses group technologies (GT – Group Technology). The essence of group technology is the grouping of products made in the production system based on technological similarity and the assignment of machines implementing the production process to individual groups of products (Forghani et al., 2014).

Machine cells are usually formed on the basis of the machine-part incidence matrix $[a_{mi}]$. Matrix $[a_{mi}]$ consists of binary elements '1' or '0'. If a_{mi} = '1' ('0'), this means that machine m performs (does not perform) an operation on part i. Initial placement of machines and parts in the matrix $[a_{mi}]$ usually does not allow to identify groups of technologically similar parts. The values '1' are spread throughout the matrix. It is required to regroup machines and parts so as to collect parts with similar structural and technological features and machines manufacturing these parts. Therefore, it is required to decompose matrix elements with values '1', so that the clusters on the diagonal of the matrix form a diagonal system (see Fig. 1). The blocks of matrix elements with values '1' created in this way are candidates for the construction of machine cells (Domański and Fertsch, 2015).

Often, the values '1' and '0' in the machine-part incidence matrix are replaced with times of implementation of individual operations on individual machines. Then these times are used for grouping purposes. The grouping process also takes into account other parameters, such as the size of the demand for individual products (Domański and Fertsch, 2015).

Adaptation of group technologies requires, above all, a solution to the problem of measuring the technological similarity of parts, the choice of methods/methods for grouping parts, and the problem of assessing the quality of solutions obtained. It is also necessary to equip the group technology cells with technological devices (in accordance with the features of the product groups assigned to the cell), which will ensure the appropriate efficiency of processing products within a given cell.

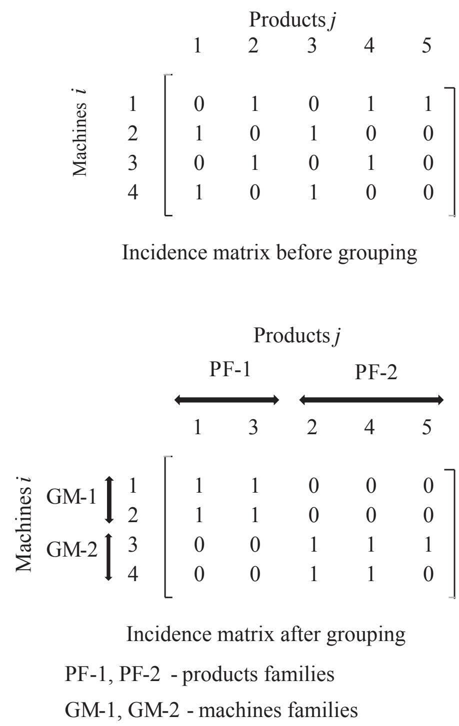

Fig. 1. Essence of process of defining machine cells (Domański and Hadaś, 2008)

In the literature you can find suggestions for many methods supporting the process of forming group technology cells:

1) informal methods (e.g., visual identification of groups), methods based on coding parts of the semi-finished part according to their characteristics (Hachicha Analysis – PCA) (Offodile, 1991),
2) classical grouping methods (hierarchical methods, k-means method, EM method (expectation-maximization algorithm) (Gunther and Tempelmeier, 2016),
3) grouping methods using similarity indicators (Domański and Hadaś, 2008),
4) artificial neural networks: self-organizing Kohonen neural networks (Setlak, 2003),
5) Adaptive Resonance Theory (ART) models (Burke and Kamal, 1995),
6) correlation analysis (Gupta et al., 2014),
7) TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and SAW (Simple Additive Weights) methods (Ahi et al., 2009),

8) graphs partitioning method including network methods (Gunther and Tempelmeier, 2016),
9) King's Algorithm (also known as Binary Ordering, Rank Order Clustering) (King, 1980),
10) Askin and Standridge Algorithm (Single-Pass Heuristic Considering Capacities) (Askin and Standridge, 1993),
11) dedicated heuristics using known properties of the analyzed problem (Cheng et al., 1998; Won and Lee, 2001),
12) metaheuristics, mainly evolutionary algorithms (Stawowy, 2006).
13) methods based on fuzzy sets theory, in particular fuzzy grouping (Susanto et al., 1999) and mathematical programming models with fuzzy parameters (Safaei et al., 2008).

The first group includes informal methods (e.g., visual identification of groups) and for obvious reasons cannot be applied to more complex problems. The same applies to methods based on coding parts of the semi-finished part according to their characteristics (Part Coding Analysis – PCA).

The majority of the remaining methods serve to group similar parts. Then, procedures are applied that allocate machines allowable in cells to individual groups of parts. They can also be used to group machines based on their similarity indicators. Among the methods from groups 11–13 there are procedures that simultaneously group products and allocate machines.

Foulds et al. (Foulds et al., 2006) showed that for more complex problems of cell formation (e.g., taking into account the possibility of making partial machine modifications) the best results can be obtained by using various heuristics, including primarily metaheuristics like simulated annealing (e.g., (Souilah, 1995)), and tabu search algorithm (e.g., (Spiliopoulos and Sofianopoulou, 2003)), as well as metaheuristics operating on a population such as all evolutionary algorithms (EA) (e.g., (Wu et al., 2007)), particle swarm optimization (PSO) (e.g., (Andrés and Lozano, 2006)), and ant colony optimization (ACO) (e.g., (Prabhaharan et al., 2004)). Other artificial intelligence methods can be used as well. One can mention artificial neural networks (mainly those based on the Adaptive Resonance Theory model (ART), e.g., (Yang and Yang, 2008)), and the fuzzy sets theory (mainly fuzzy grouping, e.g., (Susanto et al., 1999)). In recent years, there have been publications using hybrid algorithms for the problem of cell formation, e.g., a genetic algorithm with local optimization improving the part-machine cell matching (James et al., 2007).

Methods for parts grouping and methods for grouping machines into machine cells based on similarity measures can use various similarity measures. In the case of continuous arguments, these are usually: Euclidean measure, Minkowski measure, Chebyshev measure, or city block (Manhattan) measure. Whereas in the case of binary data, many similarity indicators were developed. A full review (76 proposals) and their classification using hierarchical grouping can be found in (Choi et al., 2010). In the work of Santos and Deutsch (Dos Santos and Deutsch, 2010), the PMI (Positive Matching Index) was proposed as a new measure of similarity between the set of attributes that characterize objects being grouped.

The proposals of machine cells defined by different methods should be compared using indicators that assess the quality of the solutions. The criteria for assessing solutions are formulated in various ways (Lee and Ahn, 2013). There are three principal criteria widely used in the literature (Gupta et al., 2014):

- percentage of exceptional elements (PE) and defined as the ratio of the number of exceptional elements (EE) to the number of unity elements (i.e., the total number of operations in the data matrix) (UE) in the incidence matrix:

$$PE = \frac{EE}{UE} \times 100; \tag{1}$$

- grouping efficacy (GE) defined by Chandrasekharan and Rajagopalan (Onyeocha et al., 2015) as follows:

$$GE = \alpha \times \frac{UE - EE}{\sum_{k=1}^{Q} m_k p_k} + (1-\alpha)\left(1 - \frac{EE}{m \times p - \sum_{k=1}^{Q} m_k p_k}\right), \tag{2}$$

where:

$\alpha \in [0, 1]$ – a weighting parameter ($\alpha = 0.5$ is commonly used),
m_k and p_k – denote, respectively, the number of machines in cell k and number of parts in family k,
Q – the number of cells,
m – the total number of machines,
p – the total number of parts;

- machine utilization (MU) which is defined as the frequency of visits to machines within cells:

$$MU = \frac{UE - EE}{\sum_{k=1}^{Q} m_k p_k}. \tag{3}$$

Notice that when $\alpha = 1$, the grouping efficacy (GE) coincides with machine utilization (MU).

In our analyses, we used the universal coefficient developed by Ng (Ng, 1993) described by the following formula:

$$\gamma = \frac{q(e - e_0)}{q(e + e_\nu - e_0) + (1 - q)e_0}\,, \tag{4}$$

where: e is the total number of operations in the data matrix, e_o is the number of exceptional elements, e_v is the number of voids in the diagonal blocks, and q is the weighting parameter.

If $q = 0.5$ (which is commonly used), Eq. (4) is equivalent to:

$$\gamma = \frac{e - e_0}{e + e_v}\,. \tag{5}$$

As emphasized by Papaioannou and Wilson (Papaioannou and Wilson, 2010) in the summary of the review of existing approaches to the problem of forming machine cells, most of the proposed methods consider only a single grouping criterion, and, what is most important, ignores future changes in the demand for manufactured products, not to mention changes in the product assortment. These methods in no way refer to the process of production preparation (especially in the conditions of the ETO), which makes it difficult to apply them to the methodology of designing production processes.

Industrial case

The research was carried out in one of the largest producers of sheet metal components in Europe. The company is a contract manufacturer – it produces only on order as a subsupplier of Original Equipment Manufacturer (OEM) producers.

The Company's clients are companies selling products under their own brand (co-produced) by other companies, i.e., currently the majority of European producers. Clients expect high quality, short terms and low price – in that order – and flexible handling. Low production costs in Asia cause that European contract manufacturers specialize in small-lot production or handle short-term orders. In the case of the company, the lack of proprietary products and the specifics of contract production translates to a wide portfolio of a variety of complex short-series products (High Mix, Low Volume, and High Complexity – HMLVHC).

The company serves several hundred clients in 18 countries in such industries like aerospace, defense, electronic, telecommunications, medical, pharmaceutical, energy, environmental, transport, etc. The most important markets from the Company's point of view are the most developed and technologically advanced countries of the so-called Old Union and Switzerland.

The Company's clients operate in virtually all industries. Principals do not always disclose the purpose of the components for which the services are provided. However, it is known that the Company's services result among others in precision tools, medical devices, aircraft components, bus components, ATMs, letter and parcel distribution systems, mass correspondence systems, telecommunication switching stations, telecommunications devices, and many similar.

Currently, the manufacturing industry relies heavily on outsourcing. The Company's clients focus on brand and sales management, possibly the production of the most complex elements. The production of entire devices or their components in large series is outsourced to contractual service providers.

The company is a Europe-wide contract service provider and provides more and more solutions for Original Equipment Manufacturers (OEM).

In addition, the company focuses not only on large OEMs but also on smaller equipment and machinery manufacturers, implementing small and medium series. Small OEMs due to low demand are not so much interesting for large contract manufacturers, and the Company offers them the same service parameters that large OEMs receive.

The assortment of outsourced products is changing rapidly. 1/3 of annual orders at the company apply to new or modified products. They require technical preparation of production in every case, i.e., designing of manufacturing processes and machine work programs, testing of processes prior to manufacturing.

The company annually produces 10,000 different products for its clients (OEMs producers) of which 3,000 to 4,000 products are produced for the first time. A major problem that increases the difficulty of how to properly organize production structure is the diversity of routes manufactured products. Despite the apparent similarity of the ordered products (the same materials and the same groups of operations), the course of the production process is very diverse and variable. The characteristics of routes in 2016 and 2017 in the company were compared. It turned out that 189 new routes appeared in 2017, which accounts for 35% of routes implemented in 2016. As one can see, the problem of creating production structures in the company concerns not only the diversification of the production program (which is a well-researched issue) but above all the variability of the order portfolio.

Currently, the company meets the stringent requirements of customers from the OEM sector. However, the company's management decided that production management should be upgraded to a higher level. Ultimately, the management aims to fully implement the Industry 4.0 concept. As the first step in this direction was considered the introduction of the QRM concept in order to offer OEM clients even better delivery conditions, especially in terms of product lead time.

An additional motivation for undertaking research and realizing the developed concept in practice is the fact that the company cooperates with a large number of cooperators from the SME sector, which are unable to conduct extensive development and industrial research on their own. The company's management intends to disseminate the results of research carried out in its own production plant among cooperators to improve the rules of cooperation.

In the first stage of the research, the focus was put on sheet metal parts and products made of stainless steel and aluminum. This production is performed on special machines and equipment. The production is performed in a separate building. Parts and products manufactured from stainless steel and aluminum not only need special machines and equipment, but also special craftsmanship. There are also few connections with other production units. Therefore, the plant manufacturing sheet metal parts and products made out of stainless steel and aluminum can be treated as a completely independent production plant.

For the majority of products, the production process consists of three basic phases:

- laser cutting and punching linked with deburring and grinding,
- bending,
- welding and/or spot and projection welding linked with leveling and grinding.

The discussed plant manufactures both finished products (sent directly to customers) and semi-finished products assembled in other company's cells. For this reason, some orders do not include bending or welding operations.

The implementation of most orders also requires additional operations that can be carried out in various phases of the technological process. These are operations such as:

- drilling and tapping,
- inserting and riveting,
- stud welding,
- polishing and grinding,
- shot blasting,
- assembly.

The laser welding robot is also a separate stand.

The production process has been carried out so far in classical technological cells separated by operational warehouses. This was a push solution resulting in all imperfections from the chain value perspective (unproductive storage and transport operations, too long production cycles, etc.). It was only thanks to the good organization of production management that it managed to meet production orders in a way that suited the customers' requirements. However, the push solution has significant advantages given the very high variability of the production program and the variability of the time characteristics of the routes. Separation of technological operations, which variously charge individual technological positions, with warehouses and parallel implementation of many production orders allowed for even use of machine groups and the possibility of balancing production capacities in long periods.

However, a question arose whether the change of the production structure in accordance with the principles of lean manufacturing consisting in replacing the technological structure of the cellular manufacturing concept would not cause excessive distortions in the implementation of production processes. The solution to such an unusual problem required the use of a modified method of forming cells. According to what was written in Section 3, it was necessary to propose an original production management system in the conditions of using a hybrid structure.

As part of the preparatory work for creating group technology cells, products and semi-finished products were distinguished, which are of interest in the process of forming machine cells. In addition, technological operations are distinguished, which are carried out in the production process of these products. The operation times and preparation and completion times have been determined for these products. On the basis of these data, machine-part incidence matrices were built. The production quantities in 2016 were determined and the weight of the products was estimated. These two quantities are strongly differentiated for products manufactured in the company and can affect the final solutions in the production structure.

To examine the possibility of separation of homogeneous product groups within the range produced by the analyzed company used classical clustering methods applied to the data of one year. Initial groupings for sample data from the company indicate that – among the classic and most popular methods - the best results are produced by binary ordering methods (Binary Ordering, Rank Order Clustering, and King's Algorithm), k-means, and Kohonen neural networks. The clustering quality determined by the formula (5)

for each method is presented below:
- King's Algorithm – 0.823,
- k-means method – 0.862,
- Kohonen neural networks – 0.836.

For comparison, a trial clustering was performed using the more advanced evolutionary strategy (ES) method of Stawowy (Stawowy, 2006). It is a non-specialized and non-hybridized heuristic that uses a modified permutation with separators encoding scheme and unique concept of separators movements during mutation. The average clustering coefficient γ obtained from 10 runs of this algorithm was 0.8256 (with the best value equals to 0.8581). As the results of these studies do not differ (most likely due to the data structure) from those obtained by classic methods, it was concluded that due to the widespread availability of tools for the implementation of classical methods, they will become part of the developed methodology that can be used in HMLVHC companies.

Relevant calculations were performed using the STATISTICA 13.1 program and the R language (R version 4.0.3) for the above-mentioned methods, except for King's Algorithm. Here, dedicated software developed by the authors was used. For grouping with the use of the R language, functions from the klaR cluster, EMCluster, clustMixType, and Kohonen packages were used.

The optimal number of clusters was determined in the k-means algorithm based on the criterion of minimizing the internal variability of groups. The number of clusters determined in this way was used in clustering with the use of the Kohonen neural network (10,000 iterations).

In the beginning, the k-means method was used to find the optimal number of groups. As a result, 6 groups were obtained. The number of elements in each group is presented in Table 1.

Table 1
Number of parts in groups resulting from k-means clustering

Group	Number of parts	Percent (%)
1	442	18.63
2	94	3.96
3	31	1.31
4	513	21.62
5	1002	42.23
6	291	12.26
Total	2373	100.00

The third group consisted of only 31 products, whose production process covered all technological operations. It was considered that the separation of such a group would be unjustified due to the use of the production capacity of machines in the cell intended for the production of these products. Therefore, the computation was performed for 5 groups using the k-means method and then Kohonen neural networks.

Table 2 presents the number of parts in each of the 5 groups and the number of parts in groups for which specific technological operations are carried out for groups formed by the k-means method.

Table 3 presents the number of parts in each of the 5 groups and the number of parts in groups for which specific technological operations are carried out for groups formed by using the Kohonen neural network.

Data from Tables 2 and 3 and the analysis of other conditions laid a basis for formulating the production structure in the company. The following conditions were considered:
- the numbers of products for which specific operations are carried out are very diverse, the smallest numbers are for laser welding, grinding, riveting, and shot blasting,
- cutting and bending processes occur for most products in groups, but there are exceptions:
  in the case of the Kohonen neural network:
  - in the first group, bending is carried out for about half of the parts,
  - in the second group, restraining is carried out for about 70% of the parts,

  in the case of the k-means method:
  - there are no restraining processes in group 3 and 4,
- in the case of the Kohonen neural network, 75% of the drilling and tapping processes occur in the first group where the dominant operation is cutting; in the case of the k-means method, 75% of the drilling and tapping operations occur in the first and third group; the dominant operations in the first group are cutting and bending, and the dominant operation in the third group is cutting,
- in the case of Kohonen neural network, inserting dominates in the second group; and in the case of the k-means method, in the first group; these are the largest groups, where the dominant operations are cutting and bending,
- the division into groups with welding, welding, and spot, and projection welding and sealing clearly emerges; this is particularly evident in the case of the Kohonen neural network; welding dominates in the third group, welding, and spot, and projection welding occurs in the fourth group, and sealing occurs in the fifth group.

The binary ordering method (Binary Ordering, Rank Order Clustering, and King's Algorithm) treats

Table 2
Number of parts in each of 5 groups and number of part in groups for which specific technological operations are carried out for groups formed by using the k-means method

	First group		Second group		Third group		Fourth group		Fifth group		Total	
	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]
cutting	1316	97.84	76	100.00	140	96.55	399	98.03	395	98.75	2326	98.02
bending	1345	100.00	76	100.00	0	0.00	0	0.00	400	100.00	1821	76.74
drilling & tapping	182	13.53	12	15.79	145	100.00	0	0.00	96	24.00	435	18.33
inserting	304	22.60	15	19.74	12	8.28	26	6.39	42	10.50	399	16.81
stud welding	63	4.68	71	93.42	0	0.00	11	2.70	30	7.50	175	7.37
welding	0	0.00	72	94.74	13	8.97	14	3.44	400	100.00	499	21.03
spot and projection welding	236	17.55	66	86.84	2	1.38	23	5.65	87	21.75	414	17.45
riveting	42	3.12	4	5.26	2	1.38	1	0.25	24	6.00	73	3.08
shot blasting	10	0.74	0	0.00	0	0.00	4	0.98	83	20.75	97	4.09
grinding	20	1.49	41	53.95	4	2.76	9	2.21	20	5.00	94	3.96
laser welding	8	0.59	8	10.53	0	0.00	4	0.98	1	0.25	21	0.88
# parts in group	1345	100.00	76	100.00	145	100.00	407	100.00	400	100.00	2373	100.00

Table 3
Number of parts in each of 5 groups and number of parts in groups for which specific technological operations are carried out for groups formed by Kohonen neural network

	First group		Second group		Third group		Fourth group		Fifth group		Total	
	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]
cutting	317	96.65	1279	98.08	318	96.66	152	100.00	260	100.00	2326	98.02
bending	183	55.79	934	71.63	315	95.74	152	100.00	237	91.15	1821	76.74
drilling & tapping	328	100.00	0	0.00	61	18.54	39	25.66	7	2.69	435	18.33
inserting	63	19.21	242	18.56	19	5.78	30	19.74	45	17.31	399	16.81
stud welding	3	0.91	38	2.91	40	12.16	60	39.47	34	13.08	175	7.37
welding	21	6.40	0	0.00	329	100.00	149	98.03	0	0.00	499	21.03
spot and projection welding	2	0.61	0	0.00	0	0.00	152	100.00	260	100.00	414	17.45
riveting	15	4.57	28	2.15	22	6.69	6	3.95	2	0.77	73	3.08
shot blasting	3	0.91	10	0.77	75	22.80	9	5.92	0	0.00	97	4.09
grinding	7	2.13	22	1.69	29	8.81	30	19.74	6	2.31	94	3.96
laser welding	1	0.30	8	0.61	0	0.00	9	5.92	3	1.15	21	0.88
# parts in group	328	100.00	1304	100.00	329	100.00	152	100.00	260	100.00	2373	100.00

the values stored in the machine-part incidence matrix as binary codes. The operation of the method can be described in the following steps:

1) assign the decimal number obtained from the binary code to each row (machine), assuming that the most significant bit is in the first column. Sort machines based on the obtained decimal values,
2) similarly, assign decimal numbers to each column and sort the columns based on the obtained decimal numbers.

The method, however, does not directly assign parts to the groups. The groups are formed based on the visual assessment of the results. In the considered case the parts were divided into 5 groups.

Table 4 presents the number of parts in each group and the number and the number of parts in groups for which specific technological operations are carried out for groups formed by using the binary ordering method. The analysis of data from Table 4 leads to the formulation of similar conditions as those formulated based on the results in Tables 3 and 4.

Relatively good results of the grouping of production cells measured by the indicator mentioned above confirm the thesis about the potential effectiveness of the cellular manufacturing concept. However, it should be remembered that the analyzes were based on data relating to a certain closed period. However, at the beginning of this chapter, it was indicated that the significant variability of the routes of the ordered products is of key importance for the organization of the production structure. For obvious reasons, it is not possible to change these solutions in short periods. Moreover, it should be noted that regardless of the method of grouping objects used (Tables 2, 3, 4), two cutting and bending operations are dominant in each of the formed groups. This is significantly conditioned by the concept of the organization of production.

Given the above-formulated conditions for creating the concept of the organization of production in the company, it was decided that an attempt should be made to apply a hybrid solution, i.e., to use cellular manufacturing concept in parallel with the introduction of continuous production flow at certain stages and leaving technological cells where it is justified. The proposed layout of machines is presented in Fig. 2.

The results of the numerical analysis were compared with the possibilities offered by the currently available technological solutions. The key premise for shaping the production structure in the way presented in Fig. 1 was the fact that all details undergo a cutting operation and the vast majority undergo as well

Table 4
Number of parts in each group and number and the number of parts in groups for which specific technological operations are carried out for groups formed by using binary ordering method

	First group		Second group		Third group		Fourth group		Fifth group		Total	
	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]	Number of parts w/ operation	Share [%]
cutting	539	100.00	1079	95.91	240	100.00	318	100.00	150	100.00	2326	98.06
bending	0	0.00	1112	98.84	240	100.00	318	100.00	150	100.00	1820	76.73
drilling & tapping	38	7.05	258	22.93	44	18.33	27	8.49	31	20.67	398	16.78
inserting	11	2.04	32	2.84	36	15.00	38	11.95	58	38.67	175	7.38
stud welding	17	3.15	15	1.33	0	0.00	318	100.00	149	99.33	499	21.04
welding	25	4.64	0	0.00	240	100.00	0	0.00	149	99.33	414	17.45
spot and projection welding	140	25.97	181	16.09	10	4.17	68	21.38	36	24.00	435	18.34
riveting	2	0.37	43	3.82	2	0.83	20	6.29	6	4.00	73	3.08
shot blasting	11	2.04	18	1.60	8	3.33	30	9.43	27	18.00	94	3.96
grinding	4	0.74	5	0.44	6	2.50	0	0.00	6	4.00	21	0.89
laser welding	3	0.56	13	1.16	0	0.00	72	22.64	9	6.00	97	4.09
# parts in group	539	100.00	1125	100.00	240	100.00	318	100.00	150	100.00	2372	100.00

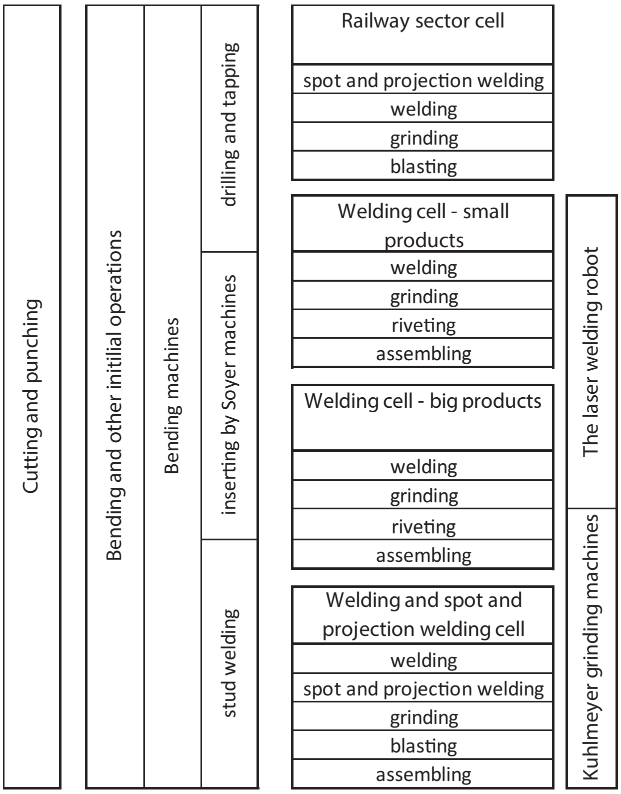

Fig. 2. Proposed layout of machines

a restraining operation. There is also a large group of products and semi-finished products that do not undergo welding, sealing, or riveting operations. Thanks to the use of the structure presented in Fig. 1, the processing of such products is significantly simplified.

The possibilities created by the purchase of technologically advanced automatic cutting and restraining devices are an additional argument for using the hybrid structure. Fully automated laser cutters will be used to control the cutting process taking into account the optimization of the pattern by combining orders (so-called "nesting") and industrial robots will be used to store sheets and cut details. Control of the cutting cell will be integrated with the ERP production management module. All of this allows for a significant shortening of the production cycle and minimizing the time of storage and transport operations while maintaining the traditional organization of production using a technological cell.

Bending operations will be carried out using modern devices that allow for computer-controlled selection and setting of tools; whereas the use of specialized software will allow to carry out operations without trials. Thanks to this, the preparatory time will be shortened to a minimum and the edging machines cell will flexibly adapt to the variability of the production program characteristic of the company. Based on the aforementioned numerical calculations and the fact that a significant part of the production program concerns products that require only cutting, bending, drilling, tapping, and inserting operations, it was decided to create a cell that joins these operations. It is also important that the production flow in this cell will be continuous, which is in line with the recommendations of lean manufacturing.

Conclusions and future works

The results of the tests and preliminary simulations carried out by the employees of the AGH Faculty of Management in cooperation with the employees of the company based on data from the company proved that the implementation of the QRM concept does not have to be associated with the absolute formation of multi-purpose cells. It turned out that the effect of reducing the response time to customer needs can be obtained by using hybrid structures that combine solutions characteristic of cellular systems with traditional systems such as a technological, linear, or mixed structure. However, this requires the use of technological solutions with the highest level of organization.

In our opinion, the proposed methodology and the results obtained indicate that the discussed solution can be successfully used in all production companies implementing the production model described in Section 4.

Currently, works are being carried out related to the adaptation of the production management system to the new structure; in particular, the development of new original algorithms, as well as dedicated planning and production preparation procedures.

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