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THE USE OF THE OPF CONCEPT IN CELL MANUFACTURING STRUCTURES

Marek Dudek, Agnieszka Zakrzewska - Bielawska

1. Introduction

Nowadays, it becomes increasingly necessary to adapt manufacturing time and conditions to the requirements and expectations of customers. This is a natural consequence of departing from the concept of a production company operating in isolation from the market needs and building an organisation directed at the needs and requirements of customers. Thus, the modern market imposes ever larger requirements on the production company. The time in which the ordered product must be delivered to a customer is constantly getting shorter. Sales are not stable, but subject to continuous fluctuations resulting, among others, from competition and the intensity of marketing operations. The dynamics of changes in the markets result in the execution of increasingly complex manufacturing tasks in a shorter time. Modern manufacturing systems which are able to fulfil these conditions are open systems capable of yielding a wide assortment of products strictly adapted to the market needs at a given moment. Such structures allow for the achievement of the highest degree of synchronizing of resource flows through the processes performed, which makes it possible to ensure a degree of continuity characteristic of a production control system called lean manufacturing [2, p. 24]. These premises became the basis for undertaking studies on the development of a procedure for job shop production flow control in small and medium enterprises. The objective of this paper is to present and verify a manufacturing system model applying the OPF concept.

2. Production flow control in workcell structures

Production workcells perform the production of a group of products[1] . These structures are characterised by the large changeability of the tasks executed as well as the flows performed. Under such circumstances, the importance of the

[1] A production workcell is a form of a manufacturing system. It is a traditional consolidated form. Consolidated structures (also called production workcells) perform the whole production process or its part on a group of similar products. They are applied in a group of stations performing different operations on a group of similar products manufactured in small lots. A production workcell may be: a flow shop (where operations may be skipped but repetitions are disallowed) or job shop (where operations may be skipped and repetitions are allowed).

production flow control increases. In order to meet the arranged times of the task completion as well as flow continuity, production flow control must involve the tracking and regulation of the following parameters:

- time of the start of a series of operations at a stage,
- number of parallel machines which perform a given operation at the same time,
- size of the transport lot.

As regards the organisation of processes, a continuous flow is the most advantageous, synchronised and with fixed times of completion. It is achievable through properly organised production space (appropriate structure) and the application of the formation of production flows. The formation of workcell processes should, apart from shortening the cycle, lead to the following:

- uniform workload of the stations in a cell,
- continuity of flows (lack of breaks at the stations),
- minimum inter-operational inventory
- correct organisation of the production space and the structure form adopted.

The uniformity of workload of the stations is achieved through the introduction of synchronisation, which is time correspondence of the production processes at the various stages of the process. Synchronisation should result in the achievement of an equal degree of occupation of the stages (the same time of completion τ_i of the same production output at each stage). The fundamental means to achieve the synchronisation of processes include:

- synchronisation through the introduction of parallel machinery,
- synchronisation through the formation of operations,
- synchronisation through the introduction of variable sizes of transport lots for a particular product at particular stages of processing (it is possible to achieve the synchronisation of processes through the introduction of variable sizes of processed lots at subsequent operations).

The continuity of flows means that no breaks occur in work at the stations. With the lack of full synchronicity at particular stages for a particular product as well as between the products in a given group, breaks in work (lack of continuity) occur at some stages. In order to eliminate these breaks, it is possible to shift all the operational series of a particular stage.

The duration of a completion cycle depends on the applied variant of flow in a given production cell. It is possible to control the flow through the change of parameters influencing the length of the production cycle. Production flow control consists of a number of operations connected with initiating the production process, monitoring its performance and controlling its flow. The main goal of the control is to manufacture products in quantities and within deadlines defined in the schedule while ensuring a continuous flow. Thus, production flow control involves such flow management that would lead to obtaining a specific quantity in a specified time period. It is possible to attain this through designing a production flow control system to ensure the appropriate synchronisation of an order.

3. Principles of production organisation consistent with the OPF

One piece flow (OPF) is a flow in one piece transport lots. This is a type of production organisation where the elements of a flow are delivered from one station to another in a manner which makes it possible to retain the flow with a simultaneous synchronisation of the process. The introduction of OPF makes it possible to [6]:

- reduce the throughput time to 80%,
- reduce the value of manufactured inventory to 60%,
- reduce the number of defects occurring during the production process to 90%,
- eliminate activities which do not add value to a product by 100%,
- balance the workload of the production workers, reduce the production space.

Besides, the introduction of OPF leads to:

- an increase in the flexibility of the process and system, which results from the possibility to change flow parameters more promptly than in batch flow,
- productivity enhancement resulting from the elimination of wastes in the flow of the process,
- an increase in the quality of products as well as the parameters of processes – an increase in the ability to control each product as well as the capability of immediate detection of a defect in the course of a process,
- enhancement of the efficiency of resources an increase in the continuity of the course of processes,
- reduction of the work in progress inventory – increase in the degree of synchronisation of processes,
- simplification of the procedure of determining demand on materials, raw materials, workshop aids, tools, etc.
- reduction of the cost of processes – reduction of stocks, waste, etc.

The implementation of such production organisation is advantageous as regards the efficiency of the system. However, it is not possible to apply one piece flow in all forms of production flow or at all stages of the production process. It is most readily applicable in flow systems (synchronous and asynchronous lines) while it is most difficult to use in non-flow forms of organisation (production workcells, technological workcells) due to the complexity of flows. As regards the cell structure, the application of one piece flow requires the engagement of an increased number of means of transport (designated on the basis of their availability, the duration of the transport cycle as well as the degree of their utilisation). The introduction of OPF rules requires the designation of an increased number of means of transport to conduct a given variant of the flow, which in industrial conditions is difficult. Thus it is necessary to consider the possibility of replacing one piece flow with batch flow between certain stages. In this case, it is important to select the size of the transport lot appropriately so as to ensure flow efficiency (which is provided by synchronicity through variable lot size at particular stages). The introduction of variable sizes of transport lots r_i for a given product at particular stages can be calculated from the formula:

$$\min r_i \leq \frac{\overline{P}}{\max a_i}$$

where:

$$\overline{P} = \frac{P}{M}$$

M – number of products manufactured,
P – volume of production of a group of products,
a_i – determines how many times the processing lot must be larger at a given stage than the processing lot at the stage with $\max \overline{t}'_{o_i}$, which is calculated from the formula:

$$a_i = \frac{\max \overline{t}'_{o_i}}{\overline{t}'_{o_i}}$$

$\min r_i$ – size of the lot at the stage with $\max a_i$

The values r_i at the other stages can be calculated from the formula:

$$r_i = a_i \cdot \min r_i$$

Synchronisation of processes results in the meeting of the following condition:

$$r_1 \cdot t'_1 = r_2 \cdot t'_2 = \ldots = r_N \cdot t'_N$$

It ensures an equal time of the processing of variable lot sizes at particular stages. The above-mentioned operations should lead to the improvement in the synchronicity and continuity of processes. The target value r_i for a given product at particular stages should be 1, as in accordance with OPF it is possible to achieve a better organisation of processes in the case of flow organisation in the form of one piece transport lots.

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4. The model of a manufacturing system with the use of the OPF concept – study results

The objective of the study was to prove the usefulness of control of the variable size of the transport lot when the OPF concept application in the cell structures is unprofitable (the application of OPF requires a type of production which is characterised by the cell distribution of machinery and tools, and the versatility of workstations) [1;7]. The above-mentioned objective was accomplished with the use of a manufacturing system model which was developed and verified on the basis of analysis conducted in electromechanical companies. The products developed in this industry are distinguished by a large constructional complexity and multi-stage production processes (products are developed as a result of the performance of successive operations described in technological routes.[2] The selection of this industry for the study is motivated by the fact that its products represent the most variable routes of technological processes and are representative of the products of other industries [5].

In order to demonstrate the usefulness of control of the variable size of transport lots while keeping the order deadline, it seems necessary to meet the following condition:

$$Cc_j \leq T_j$$

where:

Cc_j – time of execution of task *j* with a given variant of continuous flow,

T_j – scheduled date of the reception of the demanded volume of production of task *j*.

Additionally, the averaged size of transport lot $\bar{r}_j$ was introduced.

$$\bar{r}_j = \frac{\sum_{j}^{M} r_j}{M}$$

The averaged size of a transport lot is a number which determines the average size of the transport lot in integers – the same as those used for defining the volume of production. The minimum quantity of a transport lot is the limitation

[2] In the electromechanical industry, both processes of forming elements as well as assembly processes are performed. Element-forming processes are performed by means of different manufacturing technologies (e.g. casting, metal forming) with machining being the prevailing method (about 70%). Assembly processes consist of combination of parts into simple subunits, which are then combined into larger units and final products. Different production volumes as well as different types of production (volumes of production batches) with a variable assortment of production are carried out in this industry.

following from the cell structure and the maximum quantity of a transport lot is determined directly by the size of the production batch and it is assumed that the structure does not limit the upper limit of the size of a transport lot. The quantity of a transport lot is determined on the basis of the organisation of flows in the cell, the character of transport connections, the mode of work and the means of transport.

In the model, it is possible to change selected parameters which influence the completion time through modifying the time of the cycle of completion of a given task or group of tasks. The influence of the parameters on the cycle duration is demonstrated by the following formula:

$$Cc_j = r_1 \cdot \sum_{i=1}^{N-1} t_{i1} + \sum_{i=2}^{N} Sw_i + \bar{r}_j \cdot \sum_{j=1}^{M} t_{Nj}$$

where:

r_j – number of pieces in a transport lot for product *j*,

p_j – size of the lot of product *j* in pieces, $p_j = \sum r_j$

$$t_{ij} = \frac{t_{oij}}{n_{ij}}$$

t_{oij} - duration of operation *i* on product *j*,

n_{ij} - number of parallel stations to perform operation *i* of task *j*,

Sw_i – postponement of the start time of a series of operations at a given stage; $Sw_1 = 0$

It is possible to change the parameters n_{ij}, r_j, Sw_i within the limits of the flexibility of the structure of a given cell. The cell structure comprises of the number of all the stations, number of the stations of a given type as well as the transport system and its organisation resulting from the spatial arrangement of the stations. In actual conditions of the execution of flows connected with manufacturing in the cell, difficulties arise as regards the full synchronicity of flow streams and this, in turn, causes breaks in the work of stations. It is possible to achieve continuity by fixing appropriate start times of manufacturing operations at individual stages.

The study was conducted on 23 cell structures in the electromechanical industry. Table 1 presents sample data used for the simulation experiment conducted with the use of the Simul8 programme. Cell size: operations N = 17, products M = 22, transport lot $\bar{r}_j$ = 30

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Table 1. Technological routes, production volume (PV) and monthly averaged quantity of a production lot for 22 manufactured products

Strip 1	210/3	244/4					
Lever 2	2520/6	65/3	2520/7	3600/8	3600/8	2520/1	
Lever 3	178/2	135/13	59/9				
Bracket 4	10/1	17/1	32/9				
Lever 5	10/1	47/4					
Housing	1238/7	203/9	2025/7	1868/1	2250/1		
Plate 7	403/2	180/2	1130/9	1678/4			
Cover	69/1	600/11	345/11	1290/1	297/9	1152/4	1104/4
Fork 9	636/2	218/13	131/12				
Strip10	109/3	139/4	8/6				
Mandrel	446/10	842/4	1872/4	554/4			
Bracket 12	12/10	96/7	19/6	5/5	96/7		
Lever 13	2760/1	2298/1	2298/7	2298/7	2760/1		
Bracket 14	12/10	96/7	96/7	96/7			
Fork 15	212/2	175/2	94/9	12/5			
Section	421/2	7/1	1118/1	987/11	1139/1	145/9	
Tooth	59/2	6/3	2808/1	8/9	2484/1		
Plate18	64/2	8/9	71/11				
Ring	12/2	2/2	1/11				
Bracket 20	77/7	77/7	77/10	77/7	77/7		
Plate 21	20/13	70/9	52/11				
Bracket 22	12/10	96/7	96/7	96/7	96/7		

Name	PV	pj
Strip 1	700	58
Lever 2	12000	1000
Lever 3	9000	750
Bracket 4	820	68
Lever 5	500	42
Housing	12500	1042
Plate7	12000	1000
Cover	11500	958
Fork 9	10400	867
Strip10	250	21
Mandrel	12000	1000
Bracket 12	800	67
Lever 13	11500	958
Bracket 14	800	67
Fork 15	10400	867
Section	11500	958
Tooth	1000	83
Plate 18	1000	83
Ring	200	17
Bracket 20	800	67
Plate21	1000	83
Bracket 22	800	67

Source: Own study

Figure 1 presents the spatial arrangement of appliances used to conduct production processes.

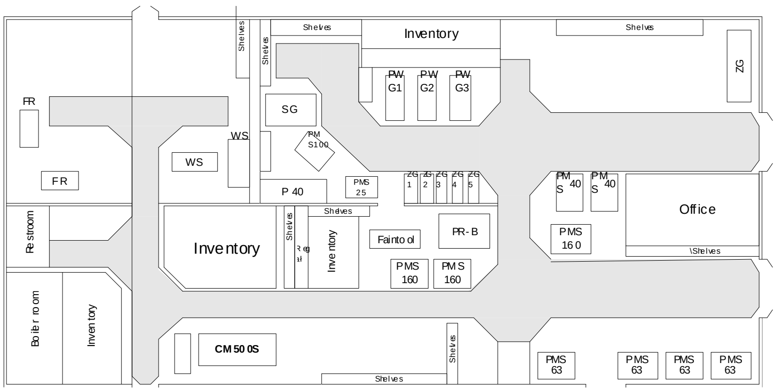

Figure 1. Spatial arrangement of elements

Source: Own research

The following coefficients were used to assess the organisation variant:

1. Process synchronisation coefficient *WZ*:

$$WZ = 1 - \frac{\sum_{i=1}^{N} St_i}{N \cdot \max \tau_i} = \frac{\sum_{i=1}^{N} \tau_i}{N \cdot \max \tau_i}$$

where:

$$St_i = \max \tau_i - \tau_i$$

$$\tau_i = \sum_j p_j \cdot t_{ij}$$

$N -$ number of process operations in the cell.

2. Flow continuity coefficient WC:

$$WC = \frac{\sum_i \tau_i}{\sum_i \tau_i^{*}}$$

where:

$$\sum_i \tau_i^{*} = C_{i,M} - C_{i-1,1}$$

It was assumed in the experiment that the number of means of transport will be determined on the basis of the time of transportation work calculated from formula [3]:

$$n_t = \frac{\tau}{Fe \cdot w1}$$

where:
τ - time necessary to perform transportation work by a given means of transport,

$$\tau = \sum t_{it}$$

t_{it} – time *i* of the transport operation,

$$t_{it} = t_j + t_z + t_r$$

t_j – driving time with and without a cargo,
t_r – unloading time,
t_w – loading time.
Fe – effective time fund of the means of transport for a specified number of changes
w1 – degree of loading of the means of transport in time $w1 = 0.5 \div 0.75$

The following values were determined for each experiment:
- values for the initial set-up (actual - at the time of measurement),

- values after the introduction of variable volumes of the transport lot (possible),
- values after the introduction of the averaged volume of the transport lot (averaged),
- values after the introduction of continuous, one piece flow (ideal).

Sixty-nine simulation experiments were carried out and their results were listed in diagrams 1-3.

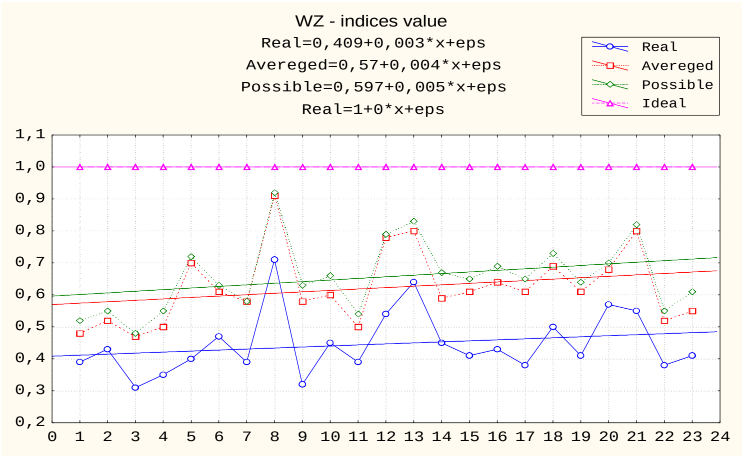

Diagram 1. Organisation coefficient value WZ
Source: Own study

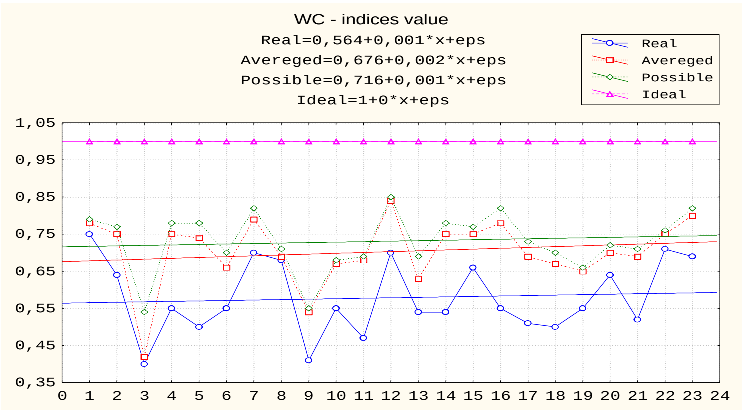

Diagram 2. Continuity coefficient value WC
Source: Own study

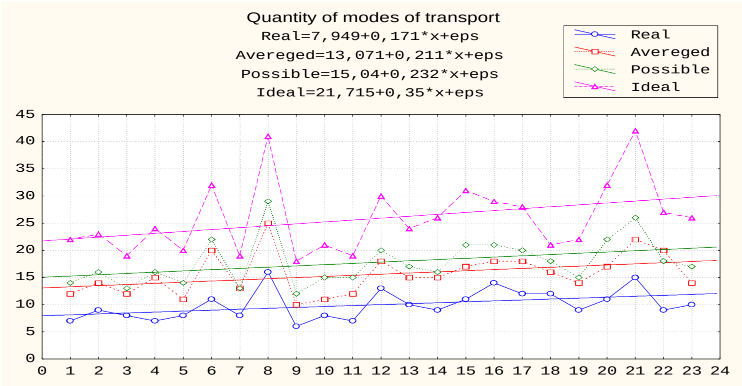

Diagram 3. Quantity of means of transport necessary to ensure the obtained values WZ and WC
Source: Own study

The above data reveal that after the implementation of streamlining, that is, changing the size of the transport lot, the synchronisation and continuity coefficients improved, which brought the process closer to the flow consistent with the OPF.

5. Conclusion

The possibility to use the OPF concept in cell structures depends on their structural flexibility. The implementation of the rigid rules of OPF requires an efficient flow of information, replaceability of the operators, the ability to dynamically shape the production space and, first of all, flow shop organisation of work with a one-piece transport lot. In the case of job shop cells, this becomes difficult to achieve. Thus, it is possible to use an intermediate variant for these structures – synchronising the process by means of the variable size of the transport lot. Such a capacity to shape flows leads to the organisation of tasks that allows for the adaptation of task completion dates to order deadlines as well as the achievement of continuous and synchronised flow streams.

The determination of coefficients and their deviations from the states accepted as the most advantageous in a specified organisation and technological conditions makes it possible to analyse the organisation of production structures as well as inter-station flows. This analysis enables conducting a programme of improvement of the existing state and bringing it close to the most advantageous time and spatial organisation of the flows. The analysis of the coefficient values which could occur following the use of the possibilities of a given cell proved that it is possible to increase them. The following goals were achieved as a consequence of the application of the procedure:

1. An increase in the organisation coefficient in comparison with the actual state:
- by 39% for the averaged transport lot,
- by 47% for the variable size of the transport lot,
- by 124% for a one-piece transport lot.

2. An increase in the continuity coefficient in comparison with the actual state:
- by 21% for the averaged transport lot,
- by 26% for the variable size of the transport lot,
- by 73% for a one-piece transport lot.

3. An increase in the quantity of necessary means of transport in comparison with the actual state:
- by 56% for the averaged transport lot,
- by 78% for the variable size of the transport lot,
- by 159% for a one-piece transport lot.

Furthermore, through simulation experiments it is possible to determine organisation patterns. Model studies make it possible to choose the most advantageous way of the realisation of the process in given conditions (they provide a process map). The simulation designing of flows allows for the analysis of a large number of possible structural configurations of a cell as well as their impact on the value of control parameters.

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