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Shaping Flexibility in Complex Manufacturing Systems

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Product customization and dynamically changing customer requirements cause multiple versions of the same product to be created with minute modifications, e.g.: different colour, material used, accessories, etc. Adapting to changing tendencies determines the manufacturer`s competitiveness. This article presents the analysis of the flexibility of a complex convergent production structure. The analysis has been conducted using the EPE (Every Part Every…) indicator. To maintain the accuracy of the system`s evaluation, the flexibility determining algorithm has been adjusted to the analyzed cell structure. A flexibility indicator EPE shows the lowest possible frequency at which the rotating production of a batch is repeated. In practice, it informs us after what time we may manufacture the same lot of goods again, taking into account the time necessary for delivering accepted orders. The conclusions from the conducted analyses helped to develop strategic development plans which assumed increasing the volume of the manufactured assortment both in number and variety.

Keywords: flexibility manufacturing, flexibility indicator EPE, convergent production structure.

1. INTRODUCTION

In modern times the company`s success on the global market is determined by its level of adaptation to the dynamically changing customer expectations [4]. In actual production facilities achieving optimal flexibility, agility and stability guarantee maximum profit [5, 2]. This article attempts to evaluate flexibility shaping in actual complex manufacturing processes. The analyses concerned a cell production structure, where a technological machine park division has been applied. The analyzed object deals with producing refrigerating appliances for a chain of stores. The final products manufactured are characterized by a wide variety of assortment, which is a result of varying customer expectations. Due to a large assortment and requirements variety, the manufacturing system analyzed within this article is characterized by the lack of production streams. The systemic approach should be taken into consideration while shaping company development plans, both strategic as tactical, and when approving long-term budgets. The purchase of new equipment (machines) should take into account the plans of expanding markets, the existing and required flexibility and efficiency of the company, and should be suited to the manufactured assortment [2]. For this reason, the investments lacking in appropriate analysis do not yield the necessary advantages and assumed profits [3].

The goal of this article is the analysis and evaluation of the flexibility of a convergent production structure. The conclusions from the conducted analyses helped to develop strategic development plans which assumed increasing the volume of the manufactured assortment both in number and variety. The evaluation was done using the EPE (Every Part Every…) indicator. For the sake of the evaluation`s precision, the algorithm determining flexibility has been adjusted to the analyzed structure. It has been assumed that EPEI determines the flexibility of a single production station (machine), EPE is the flexibility of the process which accounts for the flexibility of a group of technologically identical machines, EPEx is the flexibility of the entire analyzed production structure. Due to the fact that there are many (416) varying in types final products manufactured within the analyzed manufacturing system, and the average production lead time of a single product equals to approximately two weeks, the flexibility analyses conducted encompassed one year. Finally, the EPEx indicator was compared to the flexibility 'required by the client' LIMIT EPE, i.e. the flexibility resulting from historical data which is all the combined orders placed within the analyzed period.

2. CHARACTERISTICS OF THE ANALYZED PRODUCTION STRUCTURE

The analyzed production facility belongs to the MSP sector – small and medium enterprises. It deals in manufacturing refrigerating appliances for a store chain internationally. These products are characterized by wide variety of assortment, which stems from variable customer expectations. The manufactures assortment is individually adjusted depending on the recipient`s requirements such as size, colour, purpose: refrigerating, heating and neutral units; the cooling medium used: R290, R452A, R134A, etc. Due to a wide variety of assortment and changing customer requirements, the production system is characterized by the lack of production stream repeatability. Additionally, the final product components are not standardized which contributes to increased mura type waste. The manufactured refrigerating products consist of an average of 160 – 180 half-products, of which 60 – 65 % is manufactured within the analyzed production system. The first stage of the analysis consisted of decomposing the production system into six departments: Mechanical, Welding, Paint Shop, Insulation, Cooling and Electronics and Assembly. This division was helpful in obtaining grouped production cells which worked on technologically similar tasks.

The Mechanical Department contained laser-cutting stations, punching and pressing, deburring and bending. In the welding department the following processes take place: welding, grinding, pickling, heat-sealing and painting (not equal to the one done in the paint-shop). The paint-shop consists of an automated line complexly executing such processes as: degreasing, drying, layering the product with powder and sintering. The Insulation Department may be divided into two groups of workstations: the first insulates *D* type doors and the body, the second assigned to insolating *M* type doors. The insulation process requires high precision and care due to high quality costs generated by potential errors committed at this stage of processing. The Cooling and Electronics department is tasked with assembling the cooling and electric system along with evaporator sub-assembly. The last department is Assembly which consists of eight independent assembly lines, each of which executes the process for a specific product group.

3. FORMULATION OF THE EPEI, EPE, EPEx AND LIMIT EPE FLEXIBILITY INDICATORS

A flexibility indicator shows the lowest possible frequency at which the rotating production of a batch is repeated. In practice, it informs us after what time we may manufacture the same lot of goods again, taking into account the time necessary for delivering accepted orders [1]. Such information allows for the production compliant with the Heijunka tool. A characteristic feature of production levelling is the division of the range into batch sizes in such a manner as to increase capacity and eliminate waste. The flexibility assessment was performed with the EPE indicator, which includes: time for manufacturing the production batch [7], dependent on the dynamically changing demand, time for refitting the machinery between respective batches and OEE (Overall Equipment Effectiveness). The article analyses the cellular manufacturing design, where technologically similar machines are allocated to one manufacturing cell. On account of the above, for the purpose of the analyses, the flexibility assessment algorithm was adjusted to the characteristic features of the system. The specific indicators: EPE, EPEI, EPEx and limit EPEI define different values of flexibility. The EPEI indicator refers to the flexibility calculation for a single production workstation (single machine), whereas the EPE indicator refers to the flexibility calculation for a process, that is a group of identical machines with technologically identical manufacturing tasks. The EPEx indicator specifies the flexibility of the entire production system and LIMIT EPEI indicator defines the flexibility dependent on the demand.

The production at the facility is characterised by great variability, which is attributable to the customisation of products [7]. The varied range within the examined period included 416 different types, that is 17.88 pieces of one type of manufactured product within one the production batch on average. However, with such great variability and diversity of the demand from customers, the mean values do not reflect the actual state. Approximately 76 % of manufactured goods involved unit production – four pieces a year at most. Due to such diversity of the range, the classification was prepared of final products divided into 10 different groups according to two adopted criteria. Each group was examined in successive analyses as a family of products displaying considerable similarity. The first criterion included a number of products of one type. According to the first division criterion, three product groups were distinguished: P, Q and R. The second classification criterion was related to the cumulative production time required for manufacturing all necessary components in a specific production area. According to the second division criterion, three product groups were distinguished: *1*, *2* and *3*. Based on the adopted division criteria, 10 product groups/families were distinguished: *P.1*, *P.2*, *P.3*, *Q.1*, *Q.2*, *Q.3*, *R.1*, *R.2*, *R.3* and *S*. Group *S* included products which did not meet any of the criteria allowing their qualification as one of the other nine subgroups. Group S for the most part contains products made to order, not from the widely accessible range, requiring additional interference of the designer, such as the change of dimensions, to fully adjust all components. After the classification, for the majority of finished goods it was observed that products with the low value of demand were characterised by high variability and vice versa – in the case of products the demand for which was 120 pieces yearly, the variability indicator did not exceed 0.3.

3.1. ALGORITHM FOR SHAPING THE EPEI, EPE, EPEx AND LIMIT EPE FLEXIBILITY INDICATORS

One of the first stages of the analyses was to determine the working parameters of each workstation, that is: working time, number of working days a week, number of shifts and time of breaks during the shifts. It was necessary to determine the nominal available time, OEE indicator and effective available time. The nominal available time is the working time per shift, minus shift breaks, multiplied by the number of shifts. The formula: (1) and (2) allowed us to define the following: nominal available times (1) and effective available working times (2) for each production workstation separately. The effective available time includes the value of the OEE indicator. Table 1 presents the working parameters of a sample workstation.

$$NDC = (t_P - t_{ZP}) \cdot LZ \quad (1)$$

where: NDC – nominal available time; t_P – working time (standard 8 h); t_{ZP} – average break time per shift, LZ – number of shifts.

$$EDC = NDC \cdot OEE \quad (2)$$

where: EDC – effective available time; OEE – indicator of overall equipment effectiveness.

Table 1. Exemplary work parameter table for a single workstation.

WORKING PARAMETERS		
parameter		unit
working hours	8	h/shift
working days per week	5	days/week
shifts	3	shifts/day
breaks	0.5	h/shift
NDC	22.5	h/day
OEE	61	%
EDC	13.67	h/day
	3,431.77	h/year
working days	251	days per year

The next stage of the analyses was to determine the LPA value that is the number of refittings for sequences of products within one year. The values of refitting times $t_{C/O}$ for a specific range family were determined with the formula (3):

$$t_{C/O}^{x} = EDC - \sum_{i=1}^{n_x} OP_i \quad (3)$$

where: EDC – effective available time; OP_i – time of loading the machine with the production of one of the product families, n_x – maximum number of final products from one of the product families , x is the product family index ie.: *P.1*, *P.2*, *P.3*, *Q.1*, *Q.2*, *Q.3*, *R.1*, *R.2*, *R.3* and *S*.

Subsequently, the mean refitting time was established for a specific product family $\overline{t_{C/O}^{x}}$ and possible number of refittings in the family – MLP_x:

$$\overline{t_{C/O}^{x}} = \frac{t_{C/O}^{x}}{LPA_x} \quad (4)$$

where: LPA_x – number of all necessary change overs made in given assortment group for a product sequence.

$$MLP_x = \frac{t^x_{C/O}}{t^x_{C/O}} \quad (5)$$

where: MLP_x – possible number of change overs in the considered group: P, Q, R, S and 1,2,3.

Finally, the EPEI indicator, to determine the flexibility of a single workstation, was estimated with the formula (6): [1, 8]

$$EPEI = \frac{LPA_x}{MLP_x} \quad (6)$$

3.2. ALGORITHM FOR SHAPING THE PRODUCT FLEXIBILITY FOR A DEDICATED LINE

First, it was necessary to establish the demand Z_i for a single production line according to the formula:

$$Z_i = CLP_i - W_i \quad (7)$$

where: i – line number, CLP_i – total number of products dedicated to the line, W_i – the real number of products produced on dedicated line.

Then, the mean number was determined of production batch sizes PP_i per i – for this line, and number of the batch variations RP_i for the specific line, according to the formulas (8) and (9):

$$PP_i = \frac{Z_i}{R_i} \quad (8)$$

where: R_i– number of assortment diversity on i-th line including product families.

$$RP_i = PP - PP_i \quad (9)$$

where: PP– average number of production batch designated for all of product families.

Therefore, the flexibility for a given line EPE_i is given by the formula (9): [1]

$$EPE_i = \frac{RP_i \cdot EPE}{PP} \quad (10)$$

where: EPE– process flexibility in which dedicated lines occur.

4. DETERMINATION OF THE FLEXIBILITY INDICATORS FOR THE EXAMINED PRODUCTION SYSTEM

It is complicated to determine the EPEI indicator for the production characterised by high variability and irregularity of demand [5] ; therefore, EPEI analyses are carried out for the entire year, not for shorter periods, as it happens in most cases. The total number of final products is 7,437 pieces, whereas the range included 416 various types of products. The production batch for all product groups is approximately 18 pieces on average; to be exact, as many as 17.88 were adopted for the calculation. The range was divided into ten families of products, while the adopted classification criteria allowed the selection of groups with the similar (or even identical) manufacturing technology. This division enabled the assumption that no time was necessary for refitting between various ranges in a specific group. In order to determine the EPEI indicator for the analysed example, the theoretical algorithm was used for establishing the flexibility of the production workstations. Due to the complexity and convergence displayed by a structure of a single final product, the algorithm used to determine the EPEI workstation flexibility was adjusted to the characteristic features of the processes in question. As for the examined enterprise, the indicator was calculated for all the production workstations, taking various assumptions into account.

For instance, the following assumptions were considered for the laser cutting station: the cutting process is performed at two identical workstations; therefore, it was assumed that orders were handled at the first unoccupied machine. The effective available time was increased by adding two available times. In this system, the EPEI indicator for laser cutting was the mean indicator for two machines examined simultaneously. Such assumptions could not have been applied to bending processes; therefore, in order to determine the EPEI indicators for the bending processes, it was necessary to specify the relative demand indicator for bent elements for respective groups of final products. In each group, the mean number of devices was established according to the range variation and, thereafter, the mean number of components subject to bending processes at least at one workstation. The mean number of components included the number of elements necessary for a single final product. Subsequently, the machine and refitting times were determined for the subgroups thus established. The additional parameters to be taken into account were technical parameters of the machinery. Due to large is large. Line 7, which serves for the assembly of Group *R.3* devices, is the most flexible, whereas Group *Q.3*, with the most significantly varied products – the least.

Table 3. List of flexibility values for assembly processes.

EPEi FLEXIBILITY CALCULATION for the i-th assembly line						
Line	Product groups	Number of products in the group [pcs]	Zi	PPi [pcs/batches]	RPi	EPEi
					[pcs]	[working days]
1	P1	958	6,479	15.57	2.31	**2.06**
2	P2	1,229	6,208	14.92	2.96	**2.65**
3	P3	596	6,841	16.44	1.44	**1.28**
4	Q2	455	6,982	16.78	1.10	**0.98**
5	Q3	2,449	4,988	11.99	5.89	**5.27**
6	R2	1,428	6,009	14.44	3.44	**3.07**
7	R3	123	7,314	17.58	0.30	**0.27**
8	Q1, R1, S	199	7,238	17.40	0.48	**0.43**

dimensions of certain moulded products, the "*Bending 2*" is a workstation with a priority assigned, in other words each large-size element takes precedence at this workstation, ultimately achieving the EPEI indicator for every machine individually.

The algorithm for the calculation of the flexibility indicator for painting did not have to include many variables. As for the painting workstation, the EPEI indicator was calculated for data per day due the low variability of the process. The variability of the process lies in the number of colour changes necessary to meet the demand for different colours. The painting time for each element is the same that is 10 minutes. The refitting involves only the colour change by the proper modification of the program and activities related to it, such as the cleaning of nozzles. The time necessary for refitting is 20 minutes. During the day, the colour is changed three times on average.

Final assembly processes had other specifics. The EPEI flexibility indicator was determined for the case in which every group of products was dedicated to a specific assembly line. The calculations were performed according to the adopted algorithm for calculating the flexibility for products dedicated to each line individually; the results can be found in Table 3. By analysing the results yielded for eight assembly lines, one may notice the obvious correlation that the process flexibility is decreased when the production series

Finally, to determine the EPEI indicators for each workstation (machine), a spreadsheet was created in MS EXCEL, including the algorithm for determining the flexibility of single workstations. It was adjusted to each workstation separately due to the individual characteristics of the specific processes. Table 4 contains a sample spreadsheet for the bending process at Workstation 2.

The flexibility analyses for the entire production system did not include the *"Evaporator subassembly"* workstation due to the high value of the EPEI flexibility indicator, which flexibility stems from the technological variability of each and every final product. The EPEI indicator does not affect the flexibility of the system because its production capacity significantly exceeds all the other workstations in the examined structure. Furthermore, the operation of the *"Evaporator subassembly"* workstation is outsourced, in other words it is an organisationally separate manufacturing section. Based on the calculated EPEI indicators, a diagram (Fig. 1) was prepared, which presents the values of the indicator among the respective workstations; also, the flexibility analysis was performed for the entire production system in the examined enterprise.

Table 4. EPEI calculation sheet for the "Bending 2" workstation.

EPEi FLEXIBILITY CALCULATION for the "*Bending 2*" workstation							
Products	**Structure [%]**	**Order Z [pcs/year]**	**B/T**		**Machine load production Z [min]**	**C/O**	
			[sec]	**[min]**		**[sec]**	**[min]**
P.1	12.9	958	40	0.67	638.67	405	6.75
P.2	16.5	1,229	36	0.60	737.40	403	6.72
P.3	8.0	596	37	0.62	367.53	398	6.63
Q.1	1.8	135	38	0.63	85.50	410	6.83
Q.2	6.1	455	41	0.68	310.92	413	6.88
Q.3	32.9	2,449	36	0.60	1,469.40	402	6.70
R.1	0.2	12	37	0.62	7.40	394	6.57
R.2	19.2	1,428	38	0.63	904.40	421	7.02
R.3	1.7	123	38	0.63	77.90	414	6.90
S	0.7	52	39	0.65	33.80	408	6.80
TOTAL	100	7,437		**TOTAL**	4,632.92		

$\mathbf{t^{x}_{C/O}}$	(effective available time) – (the sum of the load)	23,548.67	[h/year]
$\mathbf{\overline{t^{x}_{C/O}}}$	(the sum of C/O) / (LPA)	0.113	[h]
$\mathbf{LPA_x}$	Number of changeovers in sequence	4,842	
$\mathbf{MLP_x}$	(time for C/O) / (average C/O)	208,395	
EPEI	(LPA) / (MLP)	0.02323	[year]
		5.83191	[working days]

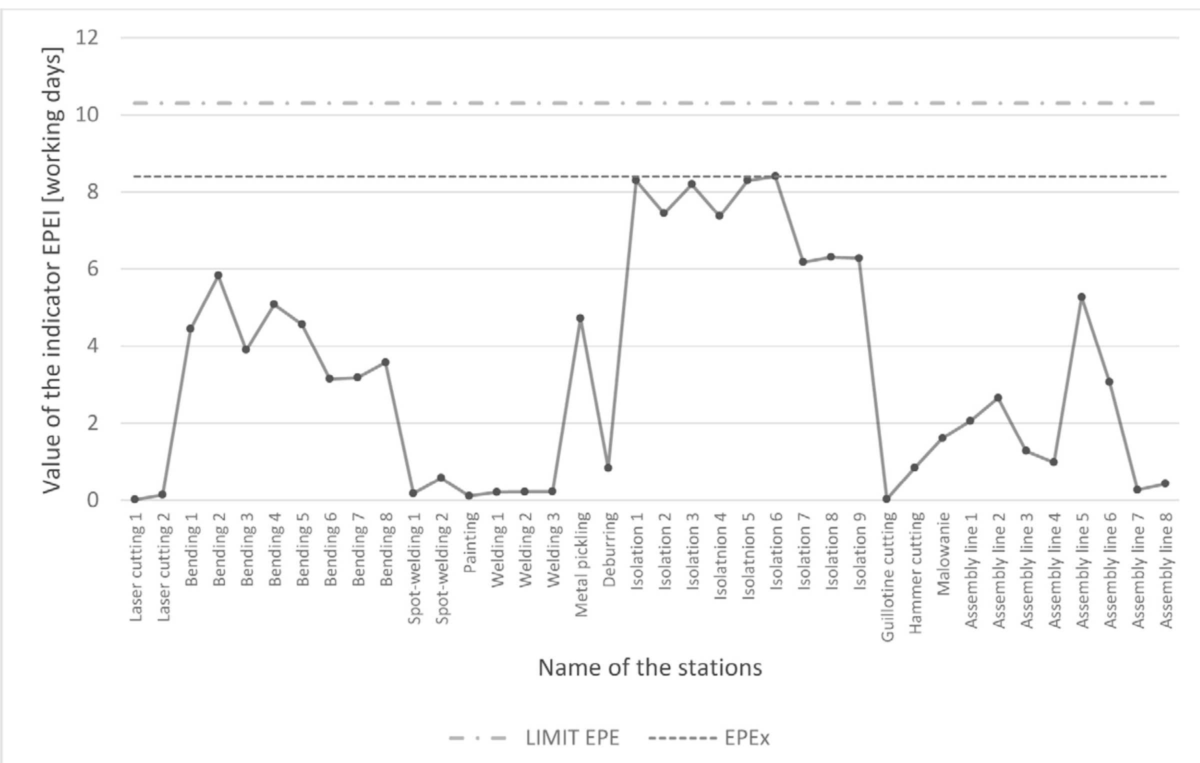

Fig. 1. Flexibility indicator for the workstation of the considered structure.

The flexibility of the entire system defined with the EPEx indicator was determined by the least flexible manufacturing process, which is the *"Isolating 6"* workstation. Hence, the EPEx indicator for the analysed manufacturing system is 8.403 working days. The flexibility required by the customer, specified with the LIMIT EPE indicator, is the difference between the time that the customer grants for handling the order and the time necessary for manufacturing the final product. According to the historical data for the period during which the analyses were performed, the required time for handling the order by the customer is 10 working days, which translates into 160 hours (with the assumption that work is performed in the two-shift system). The mean time for manufacturing the Group P.1 product is 77.5 hours. Hence, the LIMIT EPE indicator is 10.31 working days. This means that the production system does not exceed the permissible flexibility determined with the value of the LIMIT EPE indicator. The flexibility parameters of the respective workstations and processes are sufficient to meet the customer's requirements. While scheduling the production and specifying the lead time for handling orders, pay attention to the least flexible process (that is the one with the highest value of the EPEI or EPE indicator). As for Group *S* products, the production exceeds the permissible flexibility due to the fact that these are single products individually made to order. Group S is barely 0.70% of all products and, therefore, the value of the flexibility indicator should not determine the value of the flexibility indicator for the entire production structure.

5. CONCLUSION

This article evaluates a realistic manufacturing system in the aspects of processes according to the general EPE algorithm. The analyzed object is a realistic manufacturing plant with a complex cell structure in which multiple (7 437) various final products are manufactured. Due to this the EPE flexibility algorithm has been adjusted so suit the discussed system. Through the conducted analyses it may be deduced that the present production structure operates at the edge of flexibility required by the client. The highest EPEI indicator value=8.403 working days is achieved at '*Insulation 6*' workstation. The flexibility of the insulation process is the highest of the determined values, therefore the flexibility of the entire EPEx production structure equals approximately 8.5 workdays. In relation to the highest EPE indicator value the flexibility required by the client has been acquired, which is determined by the LIMIT EPE indicator equalling 10.31 workdays. To increase the number of manufactured final products of which the assortment variety structure will be determined as in the group division: *P*, *Q*, *R* and *S* and *1*, *2*, *3*; it will prove necessary to invest in a new large-sized insulation station. The process flexibility indicators value EPEI for the remaining production cells is less than 6 workdays. Therefore a critical area of the analyzed production structure due to the flexibility indicator is the insulation processes group. An assortment variability proportion change between groups which is achievable by increasing the number of final products manufactured will cause an increase in the EPEI indicator of the insulation process. At that time there exists a high probability for the flexibility indicator LIMIT EPE to be exceeded. The result would be an increase in the lead time value of production order execution as well as the lack of timely order realization. In order to avoid delivery delays it is necessary to focus on accordingly scheduling non-flexible workstations and monitor processes with the highest EPEI indicator in real-time. Ultimately it would be advisable to invest in a new workstation, which would result in increasing the flexibility of the entire structure and lessen order execution time, providing minimized WIP levels [6].

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