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A Flow-oriented Production Cell in Conditions of Low Technological-Organizational Similarity

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Abstract
This paper presents the concept and methodology for the designing of a "tree-shaped" production line. The concept is a result of the search for production unit organization that meets the Lean Production assumptions, i.e. focusing on lead time (throughput time) shortening with simultaneous ability of use in conditions of varied product range. The varied product range characterized by lower technological-organizational similarity when compared to "U-shaped" units typical for Lean Production. The paper presents an algorithm for the designing of a "tree-shaped" production line and examples of its application. The designed unit underwent evaluation according to the criteria preferred by Lean Manufacturing experts. The designed production unit achieved results confirming the effectiveness of the proposed concept for the analysed sets of input data on the product range and production capacities.

Keywords
Lean management, Production line balancing, Cellular manufacturing, Continuous flow, Layout.

Introduction

Since its inception, the Lean Management concept has been identified with efficient resource management and counteracting wastefulness, which translate into minimization of environmental impact and improved economic effectiveness. At the same time, Lean Management's strong focus on the employee, his or her talent, skills and engagement in continuous improvement makes him or her an active person, which also corresponds with social expectations. The foregoing aspects allow for the conclusions that the Lean Management concept fits into the sustainable development idea, thereby making it relevant and useful. Therefore, the unwavering interest of the Lean Management practitioners is related to the high competitive pressure and, in consequence, continuous need for seeking new methods of reducing the lead time and any wastefulness. Entities in the market are currently competing not only in terms of price (which requires cost reduction) or product quality, but also in terms of availability – and expectations concerning order processing are increasing. This can be viewed as increased expectations on order processing time reduction. Success is achieved by those enterprises that guarantee quicker deliveries, provide cheaper and higher-quality products. A focus on the reduction in stock, including work in progress (WIP) and reduction in the production lead time (throughput time) and, in consequence, order processing time reduction is viewed by managers as one of the primary benefits of implementing Lean Management into production.

Literature review

Production following the Lean Manufacturing concept takes place on production lines according to the one piece flow (Sekine, 2005) principle. The designing of such a line takes place in the following steps:

- product range selection of production line,
- station number calculation (acc. to the Assembly Line Balancing procedure) (Boysen et al., 2008),
- employee number calculation acc. to the same procedure,
- machinery layout planning.

A literature analysis provides much information on the designing of production units. In the Lean concept, the so-called U-shaped line is the most pop-

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ular. U-shaped assembly line has a better balance and a more compact space compared with traditional linear line derived from lean production. The researchers' attention focuses on the balancing problem, including various constraints and the use of mixed tools such as nonlinear programming and genetic algorithm for optimized solution (Wang et al., 2018). The objective of researchers are also, to propose a methodology for multi-objective optimization of a mixed-model assembly line balancing problem with the stochastic environment. Mathematical model was developed with objectives of minimizing lead time (throughput time) and minimization of the number of workstations (Legesse el al., 2020).

The issue of balancing the assembly line is also considered in the context of assortment selection. The assortment selection is based on the similarity criterion. Products which pass through similar processing steps and share common equipment are group into product families. Product family assembly line (PFAL) is a mixed-model assembly line on which a family of similar products can be assembled at the same time. Minimizing the number of stations, minimizing the load indexes between stations and within each station, and maximizing task-related degree are used as optimization objectives (Hou et al., 2014).

Another important issue is line layout. Linear layout is the simplest one of all layouts. L-shaped line is simple modification of linear line, s-shaped line is in turn the space can be fully used and applied to assembly line which has a wide variety of process. U-shaped layout is compact and operators can easily help each other to avoid the line of jams and realize the line balancing (Wang et al., 2018). U-shaped lines are ordinarily used in lean production systems. In U-shaped production lines, each worker handles one or more machines on the line: the worker allocation problem is to establish which machines are handled by which worker. This differs from the assembly line balancing problem in that the assignment of tasks to line locations is fixed (Shewchuk, 2008). The combination of lean manufacturing approaches and line balancing algorithms can be used to design automotive production assembly lines. This method integrates both approaches (Oattawi et al., 2019).

Performance of a manufacturing cell is dependent on an efficient layout design, and optimal work schedules. However, the operator-dependent factors such as learning, forgetting, motivation, and boredom, can considerably impact the output of the system. A meta-heuristic approach allows to solve the problem and the results compared with a static case where no human factor is included, demonstrated that such an approach can improve the performance of the cell design (Ayougha et al., 2020).

Facility layout design is one of the most frequently used efficiency improvement methods for reducing operational costs. Facility layout design deals with optimum location of facilities (workstation, machine, etc.) on the shop floor and optimum material flow between these objects. The combination of facility layout design and selected lean methods (tact-time design, line balance, cellular design and one-piece flow) allows to improve efficiency more significantly, reduce costs and improve more key performance indicator (including such as: amount of total workflow, material handling cost, total travel distance of goods, space used for assembly, number of workers, labor cost of workers and the number of Kanban stops) (Kovács, 2019).

The paper features a discussion on the designing of production units in enterprises focused on implementing the Lean Management concept in the environment of medium-sized enterprises operating in the specific machinery construction discipline. The production in this type of enterprises is characterized by the following features:

- the product range covers several groups of structurally different products,
- the annual demands are varied and feature a trend of oscillating around average, constant demands in longer value periods,
- the technologies and machinery parks are highly varied. The large range of parts and/or materials required for the production of particular product items substantially exceeds the number of unified items,
- the production is repeatable, but non-rhythmic.

The above features contribute to the inability of applying typical lean production unit (e.g. U-shaped line) designing procedures, where a linear flow compliant with the technological operations' sequence requires high product range similarity in terms of the used machinery and compliance of technological routes. As a result, it is necessary to seek other methods of production line organization, which in the conditions of lower technological-organizational similarity will still meet the key Lean Manufacturing assumption, i.e. the focus on production flow and, in consequence, shortening the lead time (throughput time).

This paper presents the concept and methodology for the designing of a "tree-shaped" production line which meets the production requirements for such conditions. The proposed method (developed algorithm of designing) was verified on numerous test data sets.

Methodology for designing a "tree-shaped" production line in the conditions of lower technological-organizational similarity

Lean Manufacturing features a linear flow in which the product range's technological-organizational similarity (understood as operation/machinery compliance) is equal to $\rho_{sr} = 0.85 \div 1$ (from 85% to 100%). For such organizational conditions, the subject of designing is a production line a variable load. Due to the method of its organization, a line-type production unit meets the "leanness" features preferred by experts including, among others (Pawlak el al., 2017):

- lead time minimization,
- work standardization (work variability limitation),
- work synchronization,
- continuous flow,
- added value index improvement.

The situation worsens in less suitable organizational conditions than those recommended for a production line. When the products' technological-organizational similarity is lower than 0.85, subject literature recommends implementing of a cellular manufacturing unit with product flow looping (Boszko, 1973). The technological-organizational similarity coefficient informs about the percentage compatibility of the types of machines required for the implementation of the production process for the analysed set of products. For example, the value of the coefficient equal to 1 (100% similarity) means that all analysed products are realized on the same types of machines. It is a unit specialized in terms of its subject (product flow) and the machinery layout does not fit into the route of all products (because particular products feature similar, but not identical routes). This type of unit does not meet all "leanness" features preferred by managers, because it includes, among others, lead time (throughput time) extension and high work variety that limits work standardization, excessive waiting for processing - an activity that does not add value, as well as high level of work in progress. This fact is the reason for the authors to take up the topic of designing an alternative production unit (meeting the preferred "leanness" features to a higher degree) in their next papers. The subject of interest is a case in which the linear similarity criteria are not met. It was therefore proposed to develop a new production organization, i.e. a "tree-shaped". The new unit will be compared with cellular manufacturing with looping to demonstrate its superiority in terms of meeting the "leanness" features. In a unit of the cellular manufacturing with flow looping type, it is possible to flow the production stream with returns to previously used machines (the layout of the machines is not in every case consistent with the sequence of technological operations for all products). In the "tree-shaped" line, the flow is always linear, with no returns (the machine layout follows the sequence of operations). Therefore, for the evaluation of the developed solution, the following measures were adopted: lead time, average work in progress (WIP), added value index and supplemented with typical measures such as: number of machines and devices engaged in the production process and average machinery load.

The designed unit should be characterized by focus on the material stream flow to minimize the lead time and limit work in progress, which is preferred by managers (Pawlak el al., 2017). The designing of a "tree-shaped" production line was made possible thanks to the development of an algorithm that specifies the steps of its creation (Fig. 1).

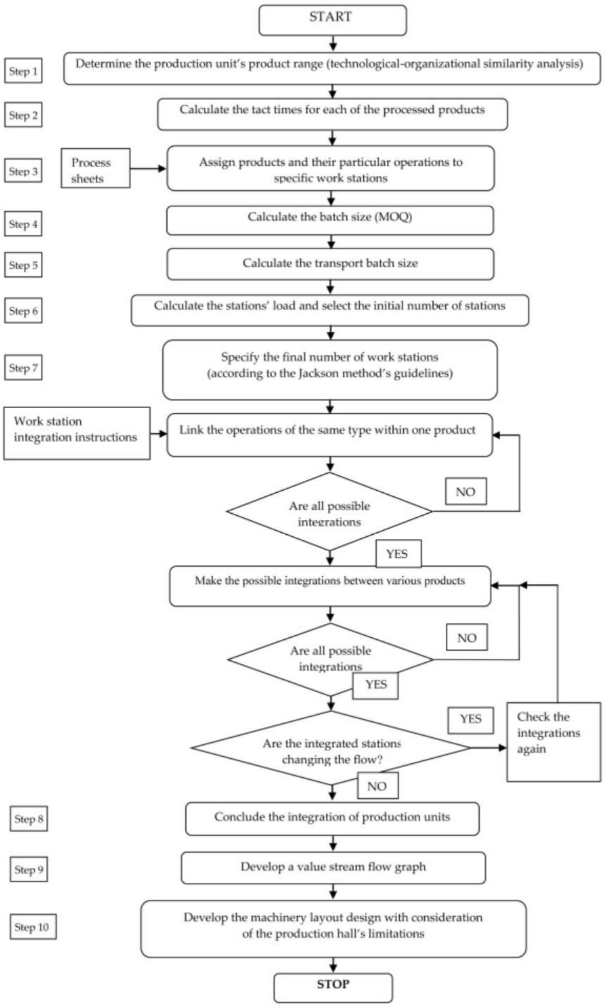

Fig. 1. "Tree-shaped" production line designing algorithm

It is necessary to determine the production unit's product range during the first designing stage. From the set of product ranges select the range that does not meet the criteria required for the production line designing due to the lower technological-organizational similarity and variable annual demand which is insufficient for the functioning of an autonomous production unit (insufficient machinery load). Then, it is necessary to calculate the tact time for each of the processed products and conduct calculations on the production batch size (insufficient machinery load). Examples with calculations are presented in Section 3.

It is possible to optimize the number of work stations in the designed production line with the use of the Jackson method (Jackson, 1956). It allows for reducing the number of stations by integrating those that perform similar operations. The Jackson method serves to calculate the optimal number of stations and its concept is as follows (Błażewicz, 1978):

- develop a set of operations that can be performed at station $j = 1$ without infringing the sequence limitations and the line rhythm,
- go to station number $j + 1$,
- develop a set of operations that can be performed at the considered station $j/ = 1$ (next) without infringing the sequence limitations and the line rhythm,
- repeat steps 2 and 3 until the operations list is exhausted.

This methodology allows for optimizing the work stations provided that the machinery is able to perform the same technological operations. The summation of unit times in operations does not exceed the tact time of the integrated stations and, equally importantly, it is prohibited to change the technological route.

It is necessary to integrate the stations in terms of the given product first and only then to integrate them in terms of the product range. It is a very simple, but useful method that substantially facilitates the work station optimization process. After determining the number of stations, their integration process is completed.

The next step featured the development of a value stream graph for the "tree-shaped" production line based on the previous calculations and technological sequence. The graph is the basis for the work station layout and plays an important role in the designing. At this stage of works, the material stream flow structure of the designed production line is transferred to the production hall with consideration of its physical limitations (room shape and dimensions, columns and transport limitations, etc.).

Verification of the developed methodology

The proposed methodology was verified on numerous test data sets. Among many analysed sets, the calculations for five examples are presented.

The first stage (step 1) featured the linear similarity calculation, which included the following checks: technological-organizational similarity, technological operations' execution sequence (which should be similar for the entire set projected in the unit) and unit times' deviations (unit times of particular operations which in perfect conditions do not differ by more than ±10%). Then, the suitable production line form was selected based on the obtained results. The products meeting the linear similarity conditions must be assigned to product groups manufactured in a synchronous line, while other products must be assigned to the product group for which the "tree-shaped" production line will be designed. The designing of autonomous production units as part of the separated groups features suitable product matching based on an analysis of the ability to use common transport means, station equipment, product dimensions, etc.

The design sets (100 product range) were selected for the "tree-shaped" production line designing process. The rejection of products with the technological-organizational similarity below 0.5 or smaller than the machinery load was sufficient to design single-range production lines. It included the linear similarity calculations and production form selection (synchronous line or "tree-shaped" line).

The sets presented in Table 1 were classified for the "tree-shaped" production line development, because their technological-organizational similarity amounted to 0.5–0.7. It was lower than the value required for the production line designing. As a result of the selection, five sets with the following products were distinguished:

- set a) product: 1, 2 and 7,
- set b) product: 11, 12 and 13
- set c) product: 71, 72 and 77
- set d) products: 32, 36, 38 and 39
- set e) products: 96, 97 and 100

Table 2 presents the technological-organizational similarity for the considered sets. The selection of the product range sets allowed for the verification of the designing methodology for sets with a various technological-organizational similarity range (from 0.53 to 0.67) and different number of products (from 3 to 4).

Table 1
Examples of product range sets and classification in production unit types

Range of products in the analysed sets	"Linear similarity" (products meeting the criterion)	Product sets classified for the "tree-shaped" type line development (considered variants)	Product sets classified for the synchronous line development (considered variants)
1–7	$\rho_{(1)avg.3i4} = 1$; $\alpha_{(2)3.4} = 1$; $\Delta t_{(3)j} = 0.67$ $\rho_{avg.5i6} = 0.875$; $\alpha_{5.6} = 0.86$; $\Delta t_j = 0.5$	$\rho_{avg.1i2} = 0.75$ $\rho_{avg.1i7} = 0.67$ $\rho_{avg.2i7} = 0.83$ $\alpha_{1.2} = 0.5$ $\alpha_{1.7} = 0.33$ $\alpha_{2.7} = 0.67$ $\rho_{sr1,2i7} = 0.67$	3 and 4 as well as 5 and 6
	$\rho_{avg.3i5} = 0.9$; $\alpha_{3.5} = 0.9$; $\Delta t_j = 0.5$ $\rho_{avg.15i16} = 0.9$; $\alpha_{4.6} = 0.9$; $\Delta t_j = 0.67$ $\rho_{avg.4i5} = 1$; $\alpha_{4,5} = 0.9$; $\Delta t_j = 0.67$ $\rho_{avg.3i6} = 0.9$; $\alpha_{3.6} = 0.9$; $\Delta t_j = 0.5$		3 and 5 as well as 4 and 6 or 4 and 5; 3 and 6
11–17	$\rho_{avg.15i16} = 1$; $\alpha_{15.16} = 1$; $\Delta t_j = 0.99$ $\rho_{avg.14i17} = 0.86$; $\alpha_{14.17} = 0.83$; $\Delta t_j = 0.94$ $\rho_{avg.14,15i176} = 0.92$; $\alpha_{14.17} = 0,92$; $\Delta t_j = 0.99$	$\rho_{avg.11i12} = 0.79$ $\rho_{avg.11i13} = 0.69$ $\rho_{avg.12i13} = 0.83$ $\rho_{avg.11,12i13} = 0.67$	15 and 16, 14 and 17 or 14, 15 and 16
32–39	$\rho_{avg33i35} = 1$; $\alpha_{33i35} = 1$; $\Delta t_j = 0.88$ $\rho_{avg.34i37} = 0.88$; $\alpha_{34i37} = 0.75$; $\Delta t_j = 0.56$	$\rho_{avg.32,36i38} = 0.73$ $\rho_{avg.32,36,38i39} = 0.58$	33 and 35; 34 and 37
71–77	$\rho_{avg.72i73} = 0.9$; $\alpha_{72i73} = 0.86$; $\Delta t_j = 0.97$ $\rho_{avg.74i77} = 0.88$; $\alpha_{74i77} = 0.56$; $\Delta t_j = 0.99$ $\rho_{avg.75i76} = 0.86$; $\alpha_{75i76} = 0.72$; $\Delta t_j = 0.88$	$\rho_{avg.71i72} = 0.77$ $\rho_{avg.71i73} = 0.67$ $\rho_{avg.71i74} = 0.67$ $\rho_{avg.71i75} = 0.67$ $\rho_{avg.71i76} = 0.6$ $\rho_{avg.71i77} = 0.64$ $\rho_{avg.71,72i77} = 0.58$	72 and 73; 74 and 77; 75 and 76
	$\rho_{avg.73i74} = 1$; $\alpha_{73i74} = 1$; $\Delta t_j = 0.96$ $\rho_{avg.75i76} = 0.86$; $\alpha_{75i76} = 0.72$; $\Delta t_j = 0.88$ $\rho_{avg.72,73i74} = 0.9$; $\alpha_{72,73i74} = 0.86$; $\Delta t_j = 0.97$	$\rho_{avg.77i72} = 0.75$ $\rho_{avg.77i73} = 0.78$ $\rho_{avg.77i74} = 0.78$ $\rho_{avg.77i75} = 0.7$ $\rho_{avg.77i76} = 0.7$	73 and 74 as well as 75 and 76 72, 73 and 74 75 and 76; 72, 73 and 74
	$\rho_{avg.73i74} = 1$; $\alpha_{73i74} = 1$; $\Delta t_j = 0.96$ $\rho_{avg.75i76} = 0.86$; $\alpha_{75i76} = 0.72$; $\Delta t_j = 0.88$		73 and 74; 75 and 76
	$\rho_{avg.72,73i74} = 0.9$; $\alpha_{72,73i74} = 0.86$; $\Delta t_j = 0.97$		72, 73 and 74
94–100	$\rho_{avg.94i95} = 1$; $\alpha_{94i95} = 1$; $\Delta t_j = 0.88$ $\rho_{avg.98i99} = 1$; $\alpha_{98i99} = 0.96$; $\Delta t_j = 0.99$	$\rho_{avg.96i97} = 0.79$ $\rho_{avg.96i100} = 0.58$ $\rho_{avg.97i100} = 0.58$ $\alpha_{96,97} = 0.56$; $\alpha_{96,100} = 0.33$; $\alpha_{97,100} = 0.22$ $\rho_{avg.96,97i100} = 0.53$	94 and 95; 98 and 99

[1] Organizational-technological similarity
[2] Technological similarity
[3] Tact time difference index $\Delta t_j = (t_{j\,\max} - t_{j\,\min})/t_{j\,\max}$

Table 2
Technological-organizational similarity in the sets

Sets of products taken into consideration	Products	Technological-organizational similarity
a	1, 2 and 7	0.67
b	11, 12 and 13	0.67
c	71, 72 and 77	0.58
d	32, 36, 38 and 39	0.58
e	96, 97 and 100	0.53

Designing of the "tree-shaped" production line according to the developed methodology (example of calculations for set "d")

Then, it is necessary to calculate the tact times (step 2) (Table 3) for the selected product range set, which are required to determine the number of work stations (Table 5).

Table 3
Product set, available working time per machine, tact time. Table with tact times for particular products

Set of products	Product	F_{mn} (Available working time / per machine) [h per annum]	P (annual demand) [pcs. per annum]	R_j (tact time) [hrs per piece]
d	32	4,032	11,200	0.36
	36		23,600	0.17
	38		39,000	0.104
	39		16,000	0.25

The next step in the "tree-shaped" production line designing is the assignment of products and their particular operations to work stations, which is featured in Table 4 (step 3).

In order to make the decision on the preliminary number of stations, it is necessary to determine the load capacity index (r_{op}) Table 4, based on which the number is adopted (step 6). The calculations featured the use of the following formula:

$$r_{\mathrm{op}_{ij}} = \frac{\sum t_{ij} \cdot P_i}{F_{\mathrm{mn}}}, \tag{1}$$

where: t_{ij} – unit labour consumption required for given operation, P_i – annual demand for i-th part, F_{mn} – Available working time / per machine, i – operation assigned to station i

The results of calculations conducted according to the design methodology (Fig. 1) are presented in the tables below (step 4 ,5, 6). The tables feature a breakdown of technological operations, assignment to machinery types, setup time, operation time, production batch, number of production transfer batch, annual demand, amount of work.

In the next step of designing, it is necessary to verify the determined number of working machines (Table 5) (step 7) based on unit times of particular operations specified in the process charts and on the calculated tact times.

When determining the number of stations, it is possible to use the collective Table 5, which features operations for each product according to the technological route. On the other hand, the determination of the number of work stations takes place in the following stages:

- specification of the duration of operations performed on particular products at given stations in the unit times' table;
- calculation of the ratio of the tact time (R_j) and the number of stations (ls). If the unit time of an operation performed on the given product exceeds the obtained ratio, it is necessary to increase the number of stations to make the time equal or smaller than the ratio of the tact time and number of stations.
- the verification of the foregoing stage's correct execution can be calculated from the time reserve (tr), which is the ratio of the tact time and the number of stations reduced by the given operation's unit time. A positive value means that the tact time for particular homogeneous station groups was chosen correctly;
- determination of the number of stations, which is adequate for the multiplicity of the tact time (TT) and unit time.

The next designing stage features the determination of the final number of work stations. Table 5 utilizes colours that show the work station integrations (step 8). Initially, the number of work stations in the selected example amounted to 27. After work station integration, the number was reduced by 7 stations for the considered set. As a result, the number of stations in the production process was reduced. The stations were integrated following the principle of aligning the loads on particular stations. For example: product 32, operation 20 is performed on 2 TUD50 machines, because the unit time is higher than the tact time. The reserve time on these machines is 0.32. In another example, product 30, operation 32 is also performed on a TUD50 machine and its t_j is 0.28. Therefore, the operation can be performed on machines that are used

Table 4
Summary table with design data

Type of machinery	Product	Operation no.	Preparatory and final time (t_{pz}) [h]	Single piece time (t_j) [h]	Order quantity (n_{org}) [pcs.]	Number of transported parts (k_t)	Annual demand (P) [pcs. per annum]	Workload ($t_j \cdot P$) [h]	Load capacity index r_{op}	Number of machines (rounded up)
TUD50 Turret lathe	32	10	0.4	0.25	39	3	11,200	2,800		
		20	0.4	0.4			11,200	4,480		
		30	0.4	0.28			11,200	3,136		
									2.58	3
TR70Bis (Universal lathe)	38	10	0.3	0.22	68	3	39,000	8,580		
									2.13	3
	32	40	0.4	0.12	39	3	11,200	1,344		
FYC26 (Milling machine)	36	10	0.3	0.19	82	3	23,600	4,484		
		20	0.3	0.05			23,600	1,180		
		50	0.3	0.07			23,600	1,652		
	39	10	0.4	0.15	28	3	16,000	2,400		
		30	0.4	0.08			16,000	1,280		
	38	20	0.3	0.07	68	3	39,000	2,730		
									3.74	4
PHW12 (Hydraulic press)	32	50	0.3	0.05	39	3	11,200	560		
	36	40	0.3	0.04	82	3	23,600	944		
	38	40	0.3	0.04	68	3	39,000	1,560		
									0.76	1
WKA25 (Drill)	32	60	0.2	0.08	39	3	11,200	896		
	36	30	0.24	0.18	82	3	23,600	4,248		
		60	0.2	0.03			23,600	708		
	38	30	0.23	0.05	68	3	39,000	1,950		
		50	0.2	0.03			39,000	1,170		
	39	20	0.2	0.16	28	3	16,000	2,560	2.86	3
Wr50 (Radial drill)	39	40	0.2	0.43		3	16,000	6,880		
									1.71	2
									13.78	16

for operation 20, because its t_j is within the reserve time. When integrating the machines, it was intended to achieve the maximum possible balance between the transitions of particular product through the production system. Another important rule that must apply when determining the stations' layout is the avoidance of the products' "looping" in the system. It is necessary to aim at maintaining the continuous flow. The designed work station layout features particular streams meeting at various points of the production system (i.e. where the stations' product load is insufficient).

The figure below (Figure 2) presents a graph which is also a representation of product flow through particular stations and the stations' preliminary layout (step 9).

Table 5
Selection of the number of stations compared to the tact time (R_j)

Product 32

number of operations	10	20	30	40	50	60
name of stations	TUD50	TUD50	TUD50	FYC26	PHW12	WKA25
type of machinery	Turret lathe	Turret lathe	Turret lathe	Milling machine	Hydraulic press	Drill
t_j [h]	0.25	0.4	0.28	0.12	0.05	0.08
$R_j \cdot l_s$ [h]	0.36	0.72	0.36	0.36	0.36	0.36
t_r [h]	0.11	0.32	0.08	0.24	0.21	0.28
number of stations [st]	1	2	1	1	1	1
tr/number of stations [h/st]	0.11	0.16	0.08	0.24	0.21	0.28

Product 36

number of operations	10	20	30	40	50	60
name of stations	FYC26	FYC26	WKA25	PHW12	FYC26	WKA25
type of machinery	Milling machine	Milling machine	Drill	Hydraulic press	Milling machine	Drill
t_j [h]	0.19	0.05	0.18	0.04	0.07	0.03
$R_j \cdot l_s$ [h]	0.34	0.17	0.34	0.17	0.17	0.17
t_r [h]	0.15	0.12	0.01	0.13	0.1	0.14
number of stations [st]	2	1	2	1	1	1
tr/number of stations [h/st]	0.095	0.12	0.01	0.13	0.1	0.14

Product 38

number of operations	10	20	30	40	50
name of stations	TR70Bis	FYC26	WKA25	PHW12	WKA25
type of machinery	Universal lathe	Milling machine	Drill	Hydraulic press	Drill
t_j [h]	0.22	0.07	0.05	0.04	0.03
$R_j \cdot l_s$ [h]	0.3	0.1	0.1	0.1	0.1
t_r [h]	0.08	0.03	0.05	0.06	0.07
number of stations [st]	3	1	1	1	1
tr/ number of stations $[h/st]$	0.027	0.03	0.05	0.06	0.07

Product 39

number of operations	10	20	30	40
name of stations	FYC 26	WKA 25	FYC 26	WR50
type of machinery	Milling machine	Drill	Milling machine	Radial drill
t_j [h]	0.15	0.16	0.08	0.43
$R_j \cdot l_s$ [h]	0.25	0.25	0.25	0.5
t_r [h]	0.1	0.09	0.17	0.5
number of stations [st]	1	1	1	2
tr/ number of stations $[h/st]$	0.1	0.09	0.17	0.25

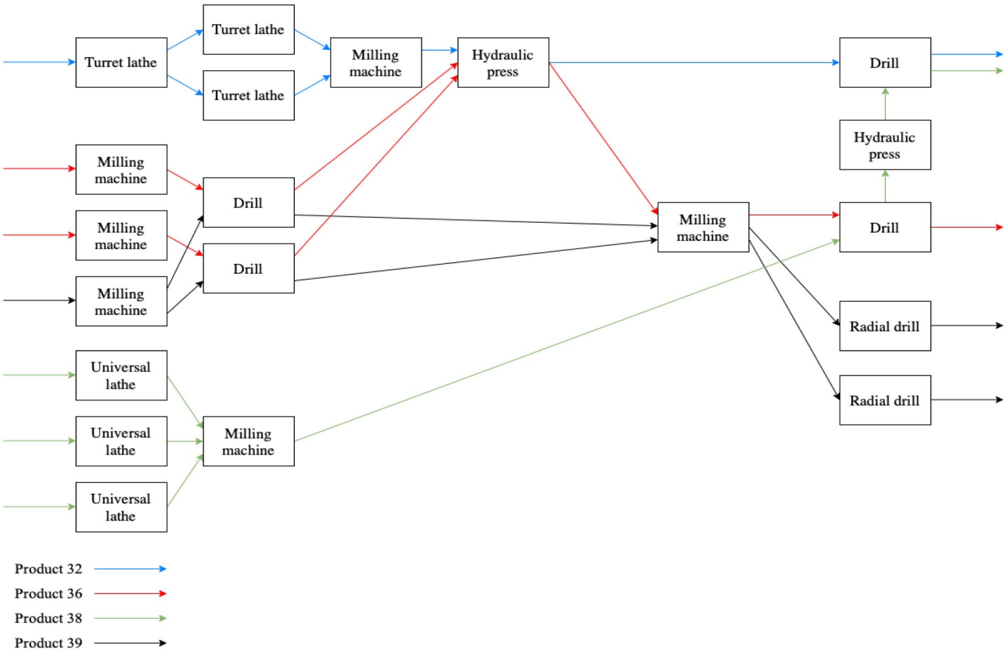

Fig. 2. Flow diagram for product set d

The graph above utilizes colours to mark the arrows showing the flow of relevant products through the machines. The obtained graph is the basis for the work stations' layout in the production hall (step 10).

Calculation of metrics and indicators for the design variants' evaluation

The next step of the works featured a comparison of the "tree-shaped" production units and the cellular manufacturing with flow looping. The comparison was made based on the calculation of metrics and indicators for the design variants' evaluation. The applied metrics and indicators as well as their weight were adopted based on a survey conducted among production managers. The managers were experienced in improving the value stream according to the Lean Management concept. The respondents pointed to the importance of the following metrics and indicators (10):

- number of machines and devices engaged in the production process,
- average machinery load,
- lead time (throughput time),
- average work in progress (WIP),
- added value index,

The first two metrics and indicators, i.e. the number of machines and devices as well as the machinery load are characteristic for the traditional unit designing. The other 4 refer to lean production units.

The numbers of machines were taken from the collective tables on calculations for the "tree-shaped" production line and cellular manufacturing with flow looping (Table 6). The average machinery load, lead time, average work in progress, added value index and average ready-to-use products were taken from the designed operation schedules for each of the production units. The machinery operation schedules included the transfer batch sizes and the FIFO rule for assigning tasks to machines.

The table below presents the comparison of metrics and indicators for the set d of designed production line.

In the analysed example, the "tree-shaped" production line achieved better results than the cellular manufacturing with flow looping. The required number of machines is an exception (increase by 2 machines). There was however an increase in the machinery's load and shortening of the lead time, which contributed to an increase in the production unit's performance, which justifies an increase in the number of stations. It also confirms the validity of such a procedure in business practice.

The comparative procedure was used for 10 designed production units (5 "tree-shaped" line and 5 reference units). The comparison of the results for all product sets and design variants is presented below (Figure 3, 4 and 5). The results in the charts are presented separately for all of the products manufactured (16 products) in the designed production units.

Table 6
Comparison of metrics and indicators set d. for designed production units

No.	Selected metrics and indicators	Cellular manufacturing with flow looping	"Tree-shaped" production line
1	Number of machines engaged in the production process	18 – calculated and adopted number of stations	16 – calculated number of stations, 20 – adopted number of stations (after correction relative to the tact time)
2.	Average machinery load	65.4%	68.5%
3.	Lead time (Through-put Time)	product 32 = 30.5 h product 36 = 33.3 h product 38 = 25.3 h product 39 = 28.3 h	product 32 = 27.8 h product 36 = 25.3 h product 38 = 22.3 h product 39 = 27.9 h
4.	Average work in progress (WIP)	WIP_{32} = 85 pcs. WIP_{36} = 195 pcs. WIP_{38} = 245 pcs. WIP_{39} = 112 pcs.	WIP_{32} = 77 pcs. WIP_{36} = 148 pcs. WIP_{38} = 216 pcs. WIP_{39} = 111 pcs.
5.	Added value index	$M_{32} = 3.87\%$ $M_{36} = 1.68\%$ $M_{38} = 1.62\%$ $M_{38} = 2.9\%$	$M_{32} = 4.25\%$ $M_{36} = 2.21\%$ $M_{38} = 1.84\%$ $M_{38} = 2.94\%$

Figure 3 below presents the production unit's total lead time for the cellular manufacturing with flow looping and for the "tree-shaped" production line in the considered examples. For each product (with the exception of set a product 1) the lead time in a "tree-shaped" production line was shortened.

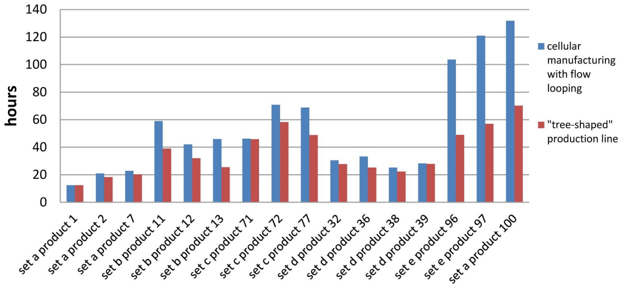

Fig. 3. Lead time for particular final products for the analysed production units

Figure 4 presents the level of work in progress for products present in the considered examples. Also in this case, there was a reduction in work in progress (WIP) for particular final products on average by 17,9%.

Figure 5 presents the percentage shares of the added value time in the total lead time of the considered examples. There has also been an improvement in the results for this aspect. Added value index increased on average by 12%.

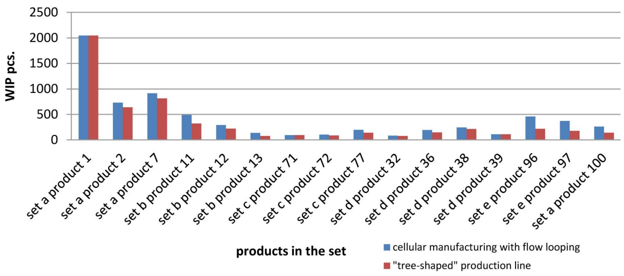

Fig. 4. Work in progress (WIP) for particular final products in the analysed production units

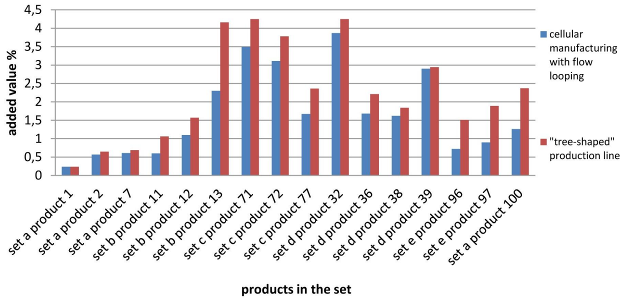

Fig. 5. Percentage share of the added value time in the total lead time of the considered production units

Conclusions

In the analysed case of the "tree-shaped" production line designing, we are dealing with a value stream fragment which is directly related to the production process execution. The impact on the value stream is based on shaping its "leanness" according to the Lean Management concept in the conditions of lower technological-organizational similarity.

As a result, the "tree-shaped" production line designing methodology was developed. Then, the proposed "tree-shaped" production line was compared with a traditional unit by calculating the metrics and indicators preferred by managers. The designed solution's validity was confirmed based on the results obtained for cellular manufacturing with flow looping and the "tree-shaped" production line (in the conditions of technological similarity lower than the value required for the line). The developed production unit is clearly flow-oriented, which is confirmed by the better results on lead time (LT) and average work in progress (WIP) than in the case of cellular manufacturing with flow looping.

Further research directions of the authors focus on the study of industry 4.0 in the context of the integration of lean tools with industry 4.0 tools in the context of eliminating waste.

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References

Ayougha A., Zandieha M., and Farhadi F. (2020), Balancing, sequencing, and job rotation scheduling of a U-shaped lean cell with dynamic operator performance, *Computers & Industrial Engineering* No. 143, pp. 1–17.

Błażewicz J., Cellary W., Słowiński R., and Węglarz J. (1978), Algorithms for controlling the division of tasks and resources in an operations' complex [in Polish], Poznan University of Technology.

Boszko J. (1973), *Enterprise organizational structure and ways of its optimization* [in Polish], Scientific and Technical Publishing House, Warsaw.

Boysen N., Fliedner M., and Scholl A. (2008), Assembly line balancing: Which model to use when? *International Journal of Production Economics*, Vol. 111, Issue 2, February, pp. 509–528.

Hou L., Wu Y.M., Lai R.S., and Tsai C.T. (2014), Product family assembly line balancing based on an improved genetic algorithm, February, *International Journal of Advanced Manufacturing Technology*, No. 7, pp. 9–12.

Jackson J.R.A. (1956), Computing procedure for a Line balancing problem, *Management Science*, Vol. 2.

Kovács G. (2019), Layout design for efficiency improvement and cost reduction, *Bulletin of the Polish Academy of Sciences Technical Sciences*, No. 3, Vol. 67, pp. 547–555.

Legesse A., Tesfaye E., and Berhan E. (2020), Multi-objective optimization of mixed model assembly line balancing in an assemble-to-order industry with stochastic environment, *International Journal of Engineering, Science and Technology,* No. 1, Vol. 12, pp. 1–15.

Qattawi A. and Sreenath Ch.M. (2019), Assembly line design using a hybrid approach of lean manufacturing and balancing models, *Production & Manufacturing Research*, Vol. 7, pp. 125–142.

Pawlak N. and Hadaś Ł. (2017), Identification of lean features in the design of the manufacturing unit, *Engineering and technology research, 24th International Conference on Production Research* (ICPR 2017), July 30–August 3, Poznan, Poland.

Sekine K. (2005), One-Piece Flow. Cell Design for Transforming the Production Process. New York: *Productivity Press*, Vol. 3–4 ISBN 1-56327-325-X.

Shewchuk J. (2008), Worker allocation in lean U-shaped production lines, *International Journal of Production Research*, No. 13, Vol. 46, 1 July, pp. 3485–3502.

Wang T., Fan R., Peng Y., and Wang X. (2018), *Optimization on mixed-flow assembly u-line balancing problem*, Springer.