Advanced Logistic Systems – Theory and Practice, Vol. 18, No. 1 (2024), pp. 107-118.
https://doi.org/10.32971/als.2024.011

DESIGN METHODOLOGY FOR THE CONTROL LOGIC OF FLEXIBLE PRODUCTION SYSTEMS AND RELATED LOGISTICS

ZSOLT MOLNAR[1] – PÉTER TAMÁS[2] – BÉLA ILLÉS[3]

Abstract: *The ever-shorter product life cycle entails a shortening of the life cycle of the production site and production systems as well. One of the biggest advantages of flexible production systems is that new products can be introduced to them continuously, so that their life cycle can be significantly extended. Flexible manufacturing systems, on the other hand, also require flexible control, the logic of which must be defined already in the design phase. The main elements of the design methodology of the production and logistics layout that make up the research are the information relationship chart and the related decision tables, which are suitable for speeding up the design and later for facilitating the creation of a digital twin and control logic programming. The paper covers an extended layout planning method which can be used to design flexible manufacturing lines.*

Keywords: *layout life cycle, flexible manufacturing, systematic layout planning, SLP-FLEX, decision tables*

1. INTRODUCTION

Today, flexibility plays an increasingly important role in all areas of our life. Flexibility is when the system handles changes in circumstances with an acceptable result in the shortest possible time. We understandably expect this flexibility in relation to production and the related logistics too.

The concept of flexible production systems has been known for a long time, but very little research deals with the design of such systems. In this paper, we examine how the famous line planning method, the Systematic Layout Planning method, should be extended to provide effective support for the design of flexible production systems. At the end of the paper, we present the application of the method on an industrial example.

2. OVERVIEW OF THE FLEXIBLE MANUFACTURING SYSTEMS (FMS)

The spread of flexible manufacturing systems became necessary due to several circumstances. In recent decades, the product portfolio of companies has grown dynamically, and more and more companies have begun to manufacture configurable, "unique" products that better meet customer needs. In addition, to pay off the expensive production machines and equipment, it has become necessary to use them as much as possible and to be able to use them for as long as possible.

In the case of flexible production systems, the emphasis is on the term “system”. The biggest advantage of flexible manufacturing systems is that they form a system and can

[1]PhD student, University of Miskolc, Institute of Logistics, Hungary
zsolt.molnar.zsolt@outlook.com
[2]associate professor, University of Miskolc, Institute of Logistics, Hungary
peter.tamas@uni-miskolc.hu
[3]university professor, University of Miskolc, Institute of Logistics, Hungary
bela.illes@uni-miskolc.hu

be designed and handled as a system. But any system can only work well when all of its components are working well.

Although there are different definitions of flexible manufacturing systems, they all agree that it's a system with three main components [1] [2]:

- production machines and equipment,
- the automatic material handling systems establishing a connection between the machines,
- and the control logic that controls the previous two and ensures the operation of the whole system.

We can distinguish 5 main types of flexible production systems depending on their design or layout [1] (Fig. 1):

- in-line or progressive
- loop
- ladder
- open field and
- robot centric

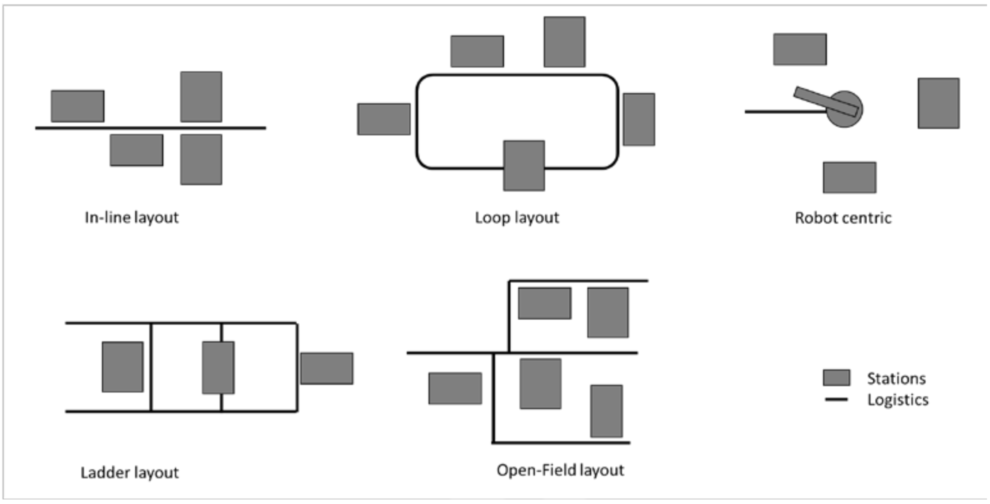


Figure 1. The 5 types of Flexible Manufacturing Systems

Looking at the schematic diagram of these layouts, it is immediately apparent that the most common material handling option for the loop, ladder and open layout is the use of AGVs [3] [4] [5].

3. DESIGNING FLEXIBLE MANUFACTURING SYSTEMS

Our developed method is based on the Systematic Layout Planning (SLP) methodology developed by Richard Muther in the 1960s [3]. This method is a detailed methodology covering the entire production line/production site planning process. Since the method supports planning with the help of data and tables, it is therefore easy to understand and suitable for digital implementation [4] [5].

The four main steps of the method are as follows [3]:

- Stage I: determining the location of the production site (in the case of a factory, this can be the site and building selection, or in the case of a production line, the selection of a location within the building)
- Stage II: general design (in this step, the basic operational concept of the production site or line, the location of the main elements and the determination of the material flow between them is happening)
- Stage III: detailed design (developing the relationships of the elements of the line, creating a detailed operating model for the machines and equipment)
- Stage IV: installation and commissioning (installation of the designed system and the start of real production after a ramp-up or preproduction period)

These four steps follow each other, but in the case of the most effective planning, there is an overlap between them, for example, it is worth looking ahead a little towards the detailed implementation during the general design and planning.

The overview process of the method is shown on the left side of Fig. 3.

The process briefly goes through the following steps. The first step in the process is to collect the data required for planning. These correspond to the PQRST pattern as follows:

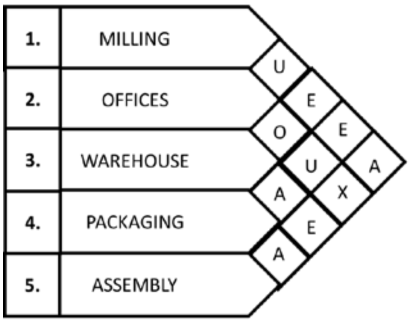
- P(roduct): the products to be manufactured and their characteristics (all attributes that can influence production are important, e.g. weight, dimensions, etc.).
- Q(uantity): the quantity to be produced, the product mix and its distribution over time.
- R(outing): the sequence of production, the succession of production processes. This is actually the Bill of Process (BOP).
- S(upporting services): this includes supporting activities, logistics, and various additional tasks, e.g. maintenance.
- T(iming): in a narrower sense, timing refers to process times and deadlines, but in the case of larger projects, deadlines for machine procurement and line planning may also appear here.

Based on this data, the so-called Activities can be defined. Activities are the places where something important from the process point of view happens. These can be machines, logistics locations, but also supporting areas (e.g. washroom, in the case of highly polluting production).

A relationship chart should be created between the individual activities, and it shows how important the proximity of each place or activity is. This proximity can be organized into categories. For example, it may be important for two production areas to be close to each other, but less important for the production area and the office to be right next to each other (Fig. 2).

The SLP method defines the following distance or proximity categories: A: absolutely necessary; E: especially important; I: important; O: ordinary closeness OK; U: unimportant; X: not desirable

It is also worth examining the material flow between activities. This can be summarized in a from-to table, which shows the amount of material flow between the individual activities in a given unit of measure. This is a matrix whose main diagonal contains all zeros. The matrix area below the diagonal could contain or refer to the backward material flow.



	1. MILLING	2. OFFICES	3. WARE-HOUSE	4. PACKA-GING	5.ASSEM-BLY
1. MILLING	-	U	E	E	A
2. OFFICES		-	O	U	X
3. WARE-HUSE			-	A	E
4. PACKA-GING				-	A
5.ASSEM-BLY					-

Figure 2. Sample relationship chart

After that, it's possible to determine how much factory space or area is needed for each activity. In the case of machines, this is relatively simple, but in the case of logistics areas, the from-to table prepared in the previous step can help a lot in the calculation or estimation.

Based on this, the space relationship diagram and different alternative layouts can be prepared. These can be compared based on many aspects (cost, work safety, practical aspects, specific needs of areas, etc.). After considering all aspects, the best layout can be selected.

When creating the space relationship diagram and layout versions, in the case of flexible production systems, logistics aspects must also be considered (transportation vehicle, pallet handling, etc.)

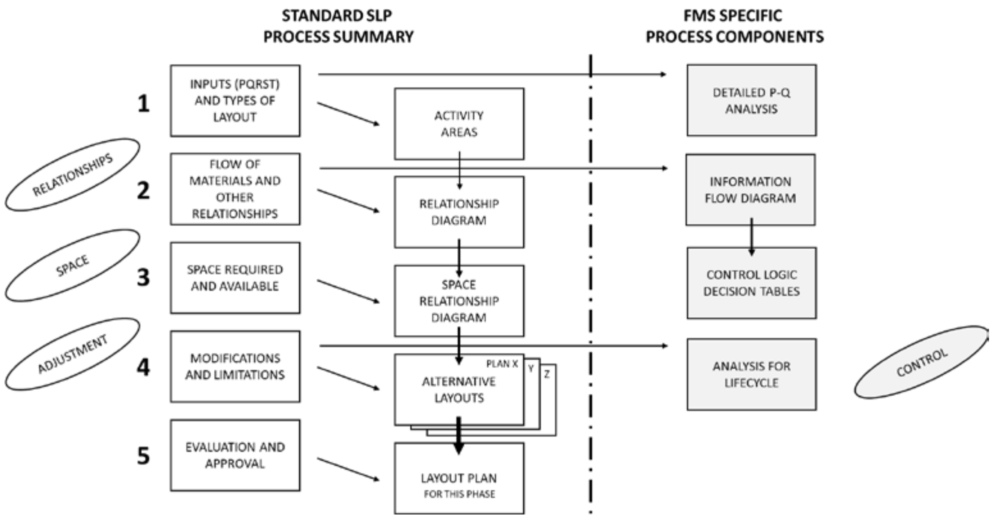


Figure 3. The SLP design process (left) extended with the SLP-FLEX design steps (right)

The SLP methodology is a general methodology and is therefore suitable for the design of any production lines, including flexible manufacturing systems. However, flexible manufacturing systems have a few special characteristics that we had to address with improvement or further development of the original SLP method.

The original SLP methodology does not deal with the following questions in relation to flexible manufacturing systems:

- the SLP method deals with production line planning but does not deal with the life cycle of the production line or its degradation in any way. Since flexible production systems are usually made for a longer period of time, for production of several product generations, it is important to examine the role of components with properties that change over time, over the life cycle of the line.
- the SLP methodology examines the main characteristics of the elements of the production line (operating time, availability, etc.), but does not deal with the information connection between the individual elements. Since control is one of the three key components of flexible manufacturing systems, it is important to take this into account during planning.
- examining the system from the point of view of the control logic, it is important that the operation of the control is transparent and that the control concept prepared during the planning can also provide assistance during the installation and later during the life cycle of the line.

4. The SLP-FLEX method

Additions to the SLP method to solve the above questions can be seen on the right side of Fig. 3. In the following section, we will explain them one by one.

Since these additions usually do not work with a static, but with a dynamic system, it is worth using some Industry 4.0 - digital twin creation tool for a complete analysis. Typically, discrete event-driven simulation is a tool [8], that provides a useful framework for modelling and testing flexible manufacturing systems. For the example in this article, we used the Siemens Plant Simulation system.

4.1. Detailed P-Q analysis

One of the most important characteristics of flexible production systems is that they are designed for a longer period than traditional production lines. Since the creation cost of the queue is higher due to the higher level of automation, it is a legitimate expectation that the queue can be used for a longer period. Typically, the life cycle of such a line is more than 10 years [4].

During this period, it is important to be able to maintain the profitability of the line. The line usually starts with a few product types, then new types are added to the number of manufactured products, while over time the production of older products ceases. In the case of flexible production systems, it is important that even after the retirement of older types, it is possible to manufacture them again, for example, if a replacement part or a spare part is needed. The life cycle of the products can be summarized in a table (Table I), and then represented in a graph (Fig. 4).

The table shows the product types and time periods. Depending on the detail of the available data, the time bucket can be years, months, or even weeks in the case of products with a short life cycle. Profit is not only determined by the number of produced parts but also by the state of the product in the lifecycle (for example in the ramp-up phase the profit is normally much higher than at the end of the lifecycle). The table also helps in estimating profitability by assigning profit values to the products. Looking at each time period in the table, you can also see the product mix that must be produced in the given period.

Table I.

P-Q analysis table

Type/Time period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
T1	100	200	400	1000	1200	900	600	150	0
T2	50	100	300	500	400	200	20	0	0
T3	0	0	0	200	400	600	1400	800	600
T4	0	0	0	0	0	150	300	600	1200

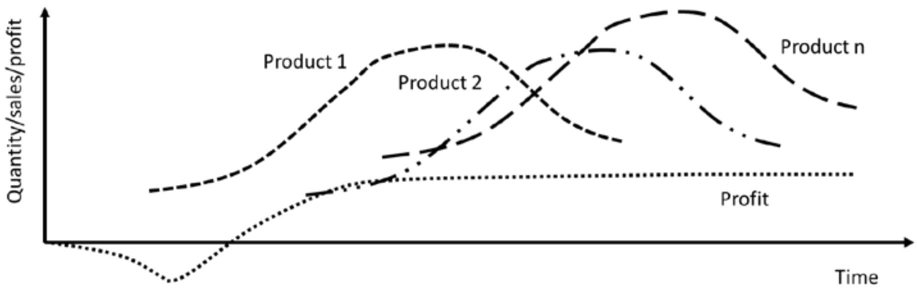


Figure 4. The Product-Quantity analysis is an important part for profitability analysis

4.2. Information flow diagram

When presenting the basics of the SLP methodology in the previous chapter, we saw that the relationship diagram is a useful and important tool for determining the position of the individual elements of the line.

The most important element of flexible production systems is the control logic which ensures the operation of the line. During the further development of the SLP method, we introduced the Information flow diagram, which shows the required information connections between individual elements of the production line. A significant difference compared to the relationship diagram is not only can machines and main activity points be displayed in this diagram, but also any device that provides or receives information. The device could be a robot or an AGV for example.

The information flow diagram can also be represented in table form (Table II).

There is relatively little space in the table, so it is usually only worth marking the existence of the information flow there. This is also a kind of From/To table, in which the part above the diagonal shows the column->row direction, and the part below the diagonal shows the row->column direction of the information flow.

Table II.

Sample Information flow relationship diagram

From/to	**1. Milling**	**2. Offices**	**3. Warehouse**	**4. Packaging**	**5. Assembly**	**6. AGV**
1. Milling	-	F1				
2. Offices	F2	-				
3. Warehouse			-			F4
4. Packaging				-		
5. Assembly					-	
6. AGV	F3					-

It is easy to see, what is the possible maximum number of information connections:

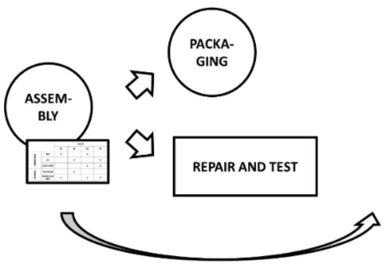
*TOTAL NUMBER OF INFORMAION CONNECTIONS = N * (N – 1)*

where N is the number of elements of the production line participating in information exchange.

The detailed information flow description can be written in text or with decision tables. For example, there could be a text description between Offices and Milling (F1) that the production plan should be published from the office to production. The opposite direction (F2) can be the production feedback information. The milling department must notify the AGVs (F3) of the completed parts for delivery. The AGVs report the parts that have arrived in the warehouse (F4).

4.3. Control logic decision tables

Another option for describing the control relationship between two production or information elements is decision tables [5]. Decision tables are an excellent tool for describing control logic. The decision tables consist of two main parts, the conditions, and the actions to be performed if the conditions are met.



		RULES			
		R1	R2	R3	R4
CONDITIONS	NIO	X		X	
	IO		X		X
	EVERY 10TH			X	X
ACTIONS	PACKAGING		X		
	REPAIR AND TEST	X		X	X

Figure 5. Simple process and it's decision table

A simple decision table can be seen in Fig. 5, where after an assembly, the part continues on the routing based on the decision table. The rule is that every 10th part must be tested, and the wrong parts (NIO) also go to the repair station which is integrated with the test function. The good parts (IO), which are not 10th parts, continue their way to the packaging. This example also shows that decision tables are a great help in building logic during planning. After the planning is completed, the logic based on the decision tables provides outstanding help during the PLC programming and production control and during the installation of the line.

4.4. Analysis for lifecycle

Flexible production systems are built to be used for a longer time, than traditional production lines [6]. Therefore, during planning, it is worthwhile to examine whether there are components in the system whose performance changes during the life cycle [7]. If the performance changes, it must be checked whether the performance level can be restored to the original planned parameters. If not, the system with reduced capacity must also be considered during the planning and sizing of the system.

In the case of flexible manufacturing system projects, it is also important how complex the finished system will be. By entering the number of rules of the related decision tables into the fields of the previously introduced information flow diagram and summing up the elements of the resulting information flow diagram, we get a metric that clearly indicates the complexity of the system.

Based on the above, let $\underline{M}$ denote the information flow diagram as a matrix, then the elements of the matrix can be written as follows:

$$M = [d_{i,j}], \qquad where\ 1 \le i \le n\ and\ 1 \le j \le m$$

where

n, m – the number of the line objects, as n = m therefore the matrix is quadratic,

$d_{i,j}$ – the number of rules of the decision table related to column i and row j.

There are no elements in the main diagonal of the matrix (their value is zero).

Based on this, the value of the C metric indicating the complexity of the system can be determined in the following way:

$$C = \sum d_{i,j}$$

The higher this number, the greater the complexity of the system.

A similarly good measure of the complexity of a flexible production system is the average number of decision rules in the system, which can be described as follows:

$$D_{average} = C/n$$

This performance indicator could work well for systems with many machines but simple logic and for systems with several machines but very complex logics too.

5. SLP-FLEX application example

To demonstrate the SLP and the SLP-FLEX method, let's look at a simple example. The production line in the example is a robot-centric production line, which is probably the simplest type of flexible production systems in terms of design.

During the development of the example, we used the Siemens Plant Simulation discrete event based simulation system [4] [5]. This system is a modern tool to build the digital twin of manufacturing systems, and scenarios [7] [6]

As we wrote the control logic before, the decision tables can be designed on paper, but since the operation is dynamic, we used a simulation tool for testing and validation. Simulation also helps to make sure that the invented control logic will work in real life.

The production line makes plastic parts, the first step of the process is 3D printing, which receives the granules from a tank. This is followed by machining, and then the process ends with a measurement. Machining is done on two machines. Production times depend on the product type.

Since the cell is robot-centric, a relationship chart (Table III) can be easily prepared. The two main considerations during the preparation are:

1. the consecutive operations should be close to each other and
2. the robot reaches all the stations from and to which it needs to pack parts.

Table III.

Relationship chart for the sample FMS line

	Raw material tank	**3D Printer**	**Machining 1**	**Machining 2**	**Measure-ment**	**Robot**
Raw material tank		A	U	U	U	X
3D Printer			I	I	U	E
Machining1				O	I	E
Machining2					I	E
Measurement						E
Robot						

Based on this data, the following layout or arrangement (Fig. 6) can be prepared. Due to the distances, in addition to the originally planned equipment and tools, an extra robot was needed between the 3D printing and the conveyor leading to the machining machines.

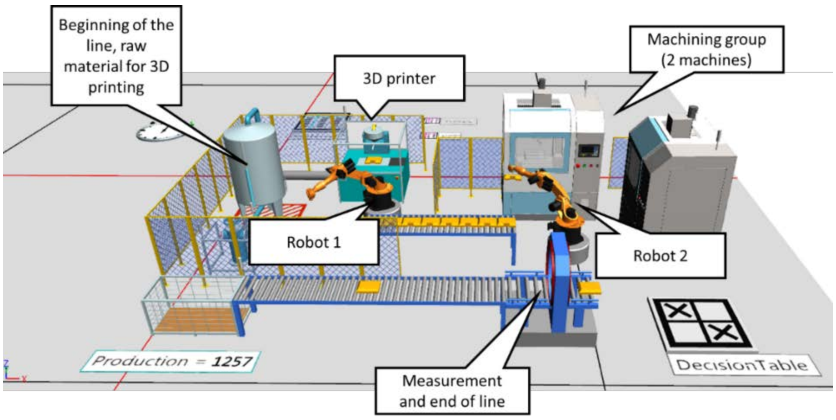


Figure 6. The layout of the sample FMS line

The information connection table shows which devices and equipment communicate with each other (Table IV). In this case, these are the functions that allow one station to check if the next station is available for the further transfer of the part.

Table IV.

Information relationship chart for the sample line

	Raw material tank	3D Printer	Machining 1	Machining 2	Measure-ment	Robot 1	Robot 2
Raw material tank		X					
3D Printer			X	X		X	
Machining1					X		X
Machining2					X		X
Measurement							X
Robot 1							
Robot 2							

The production line is designed for at least 8 years, but already in the first year the line must be able to produce all types according to the Product-Quantity table below (Fig. 7).

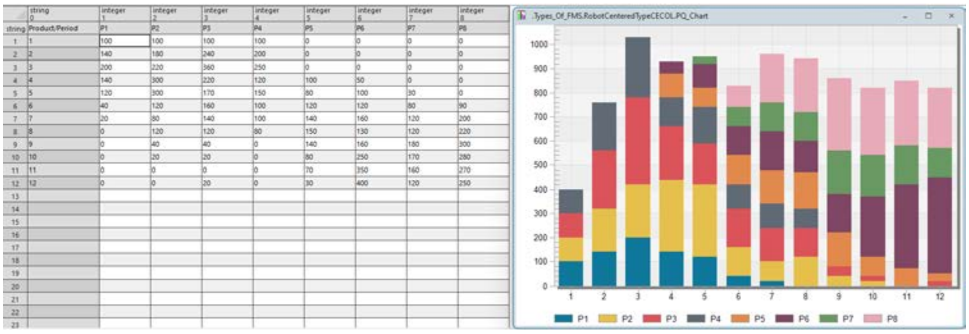


Figure 7. P-Q analysis of the sample line

It can be seen from the data that the flexible production system is really needed, there are months when only 4 types are produced, there are times when 7 types out of 8 are in production.

There are two main approaches to building decision tables. Each decision location can have its own decision table, or in the case of simpler systems, the entire control can be collected in one central decision table. In this example, we chose the central decision table, in which the condition filters to which station the given decision logic is connected.

The completed decision table (Fig. 8) can be easily interpreted even with minimal programming knowledge. It was possible to describe the control of the entire system with three rules. In each case, we look at which condition the given rule will be active upon fulfilment, and then we look at what happens when the given rule is activated. Let's look at them in detail below:

- Rule 1: the condition is that once a part has been completed on the 3D printer. In this case, the next stop of the part is the conveyor, to which it is sent. We didn't care about controlling the robot 1, the control system handles it automatically based on the "destination" attribute.

- Rule 2: the condition is that a part from 3D printing has arrived at the end of the conveyor and ready to move on to the next operation, the machining. In order to proceed, it is necessary that either the Machining1 or Machining2 machine is empty, and that the robot 2 is also empty, i.e. able to forward the part. If this is met, the part is transferred to the free machine.
- Rule 3: the condition is that a part has been completed on one of the machining machines. Then, if the measuring machine is free and the robot 2 is also free to transfer the part, the part goes on to the measuring machine.

	string 0	string 1	string 2	string 3
string	Collecting Conditions	R1	R2	R3
1	CONDITIONS			
2	makepathrelative(@.location)="Machining1" or makepathrelative(@.location)="Machining2"			X
3	makepathrelative(@.location)="Printer3D"	X		
4	makepathrelative(@.location)="Conveyor"		X	
5	ACTIONS			
6	@.destination:=Conveyor	X		
7	@.move	X		
8	waituntil (Machining1.empty or Machining2.empty) and PickAndPlace.empty prio 2		X	
9	if Machining1.empty then @.destination:=Machining1 end		X	
10	if Machining2.empty then @.destination:=Machining2 end		X	
11	@.move		X	
12	waituntil Measure.empty and PickAndPlace.empty prio 1			X
13	@.destination:=Measure			X
14	@.move			X

Figure 8. Decision table for the sample line

These three rules are suitable for describing the operation of the system. Apparently, in case of any line changes, the logic can be easily modified, and if necessary, several control variations can be easily tried.

6. CONCLUSION AND SUMMARY

In this article, we provided a solution to the special elements of planning flexible production systems by further developing the Systematic Layout Planning method and implementing it in a digital twin. It is clear from the example that SLP-FLEX, inheriting the advantages of the SLP method, complements it with the specific design areas of flexible production systems. The SLP-FLEX method is data-based, so it is also suitable for creating digital twin mapping.

Another big advantage of SLP and the improved SLP-FLEX method is that it uses a unified data model, so that flexible production system design projects within a company are transparent to the entire group. In this way, the speed of collaboration and cooperation between teams can be greatly increased in the case of design projects, making planning more flexible and planning time shortened. The developed method is industry-ready, gives a handy framework for the line planners and line designers to develop production ready flexible manufacturing systems.

REFERENCES

[1] Muther, R. & Hales, L. (2015). *Systematic Layout Planning*, Management & Industrial Research Publications, Marietta, USA

[2] Molnár, Zs., Tamás, P. & Illés, B. (2021). The Life cycle of the layouts of flexible and reconfigurable manufacturing areas and lines. *Advanced Logistic Systems – Theory and Practice* **15**(1), 20-29, https://doi.org/10.32971/als.2021.003

[3] Mohamed, Z. M. (1994). *Flexible Manufacturing Systems: Planning Issues and Solutions.* Garland Publishing Inc.

[4] Sujová, E., Střihavková, E. & Čierna, H. (2018). An Analysis of the Assembly Line Modernization by Using Simulation Software. *Manufacturing Technology* **18**(5), 839-845, https://doi.org/10.21062/ujep/187.2018/a/1213-2489/MT/18/5/839

[5] Greenwood, N. R. (1988). *Implementing Flexible Manufacturing Systems*, London: Macmillan Education LTD, https://doi.org/10.1007/978-1-349-07959-9

[6] Shivanand, H. K., Benal, M. M. & Koti, V. (2006). *Flexible Manufacturing System*. New Delhi: New Age International Limited

[7] Bangsowmi, A. (2020). Tecnomatix Plant Simulation Modeling and Programming by Means of Examples. Second Edition, Springer Cham, https://doi.org/10.1007/978-3-030-41544-0

[8] Musil, M., Laskovský, V. & Fialek, P. (2016). Analysis of logistic processes using the software tecnomatix plant simulation. 13th International Conference on Industrial Logistics, ICIL 2016 - Conference Proceedings, 195-200.

[9] Abanda, F., Jian, N., Adukpo, S., Tuhaise, V. & Manjia, M. (2024). Digital twin for product versus project lifecycles' development in manufacturing and construction industries. *Journal of Intelligent Manufacturing* 1-31, https://doi.org/10.1007/s10845-023-02301-2

[10] Halassy, B. & Zentay, T. (1973). *Döntési táblázatok*. Nemzetközi Számítástechnikai Oktató Központ, Budapest

[11] Soori, M., Arezoo, B. & Dastres, R. (2023). Digital Twin for Smart Manufacturing, A Review. *Sustainable Manufacturing and Service Economics* **2**, 100017, https://doi.org/10.1016/j.smse.2023.100017

[12] S. K. R. (1986). Flexible Manufacturing Systems: An Industry Overview. *Production and inventory management* **27**(4), 1-9, Washington, D.C.

[13] Gubán, M., Kovács, G. & Kot, S. (2017). Simulation of Complex Logistical Service Processes. *Management and Production Engineering Review* **8**(2), 19-29, https://doi.org/10.1515/mper-2017-0014

[14] Prasad, B. & Srivastava, R. K. (2018). Comparative Analysis of Procedural Approaches for Facility Layout design using AHP technique. *International Journal of Applied Engineering Research* **13**(9), 238-243.

[15] Alvarado-Pajares, M., Bautista-Choquehuanca, D. & Leon Chavarri, C. (2022). Design of a Production System using 5S, SLP and Work Study to Increase Productivity at a Bakery SME. Proceedings - 2022 8th International Conference on Information Management, ICIM 2022, 160-165, https://doi.org/10.1109/ICIM56520.2022.00036