Enhancing productivity: A comparative case study of Fishbone vs Parallel Assembly Lines

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Abstract: As consumers, there is a growing tendency to desire customised products. However, for producers, fulfilling this desire is not as straightforward. Mass customisation brings significant changes to manufacturing environment and assembly systems. Traditional assembly methods are no longer sufficient to meet the high variety of products demanded by the market in reasonable timeframes and budgets. Consequently, many new alternatives are emerging to optimise assembly processes, maintain competitiveness in the market, and address the need for high flexibility. This article focuses on comparing the productivity of two different assembly systems within a multi-model strategy. On one side, the parallel straight-line assembly system with fixed workers is proposed, while on the other side, a more flexible solution is presented: the fishbone assembly line, a line with parallel workstations. The unique feature of the fishbone system is the presence of a central backbone that allows parts to pass from one side of the line to the other, minimising waiting times. Since both strategies are entirely manual, the article aims to compare these two systems by taking into account the possible diverse efficiency rates of the workers, through a simulation study. Real data from an Italian company have been used to perform the comparison. The results show that the fishbone system can reach a 13% higher productivity than the parallel straight-line assembly system in certain situations. In particular, the fishbone assembly line outperforms the system with parallel lines in terms of productivity when the workers in the same stage of the line have different efficiency levels. If all operators have the same efficiency level and the processing time of the products is similar for each of them, or there are big batches, the two systems are almost equivalent.

Keywords: assembly system, parallel lines, parallel workstations, fishbone layout, comparison

1.Introduction

The need to always have more different and customised products is spreading fast in society, leading companies to profoundly reconsider the way they produce. The production strategy is shifting from mass production to mass customisation, so traditional assembly systems designed for mass production no longer provide the flexibility required by today's market needs (Lian et al. 2018). In addition to traditional assembly lines, there are many different alternatives in terms of layout and workforce strategies that can be implemented in an industry to address the changing market conditions (Hashemi-Petroodi et al. 2021; Ren and Tang 2022; Yılmaz 2020; Catalano et al. 2023).

In particular, workforce strategy is an essential point to take into account in order to improve flexibility, since workers are the main protagonists of the assembly systems and they are by nature the greatest source of flexibility: they learn quickly and can carry out very different operations (Zaeh et al. 2009). An important reference on worker deployment and possible workforce reconfiguration strategies is the review by Hashemi-Petroodi et al. (2021), which clearly shows how workers can improve the flexibility and reconfigurability of the system. Choosing the most suitable workforce strategy is a crucial decision in the assembly system design phase, but it is also important to include the workers as human beings. In fact, each worker is unique and must be considered as such to avoid mistakes in forecasting or sizing the system (Gino and Pisano 2008). Diversity can be considered in terms of ergonomics (Katiraee et al. 2021), training, skills, efficiency, or even human behaviour (Gino and Pisano 2008). In the literature there are not enough studies that include these characteristics in the systems design process, and this fact often leads to unrealistic results or difficult-to-implement models (Gino and Pisano 2008). This complicates the already challenging task of selecting the best assembly system to implement, as there are many options in the literature, but no simple decision-making tools to guide the selection of the best layout and workforce strategy for the system under analysis, as reported in (Al-Zuheri et al. 2010), especially when the employed workers are heterogeneous (Catalano et al. 2023).

The layout of an assembly system is often determined by the production strategy and includes everything related to the assembly process: the position of the workstations, the type of the connection system between stations, the system feeding policy, etc. In today's context, where production flexibility is the main objective, the right layout choice has become crucial (Al-Zuheri et al. 2013), as is the choice of workforce strategy (Hashemi-Petroodi et al. 2021). Indeed, if the traditional straight assembly line is preferable for mass production, other configurations need to be evaluated in the case of mass customisation. Among these innovative solutions is the fishbone layout, which consists of a central backbone connecting parallel workstations. The main difference between the parallel straight-line layout and the fishbone layout is the ability to adhere to the entry order of the parts. In the case of the fishbone layout, thanks to crossovers (Aguilar et al. 2020), parts can overtake each other, reducing the waiting times that often occur in a classic linear system, thus increasing the flexibility of the system.

In this context, this study presents a comparison between these two different layouts to understand which configuration is better for a real case scenario to achieve higher productivity rate. The main focus of the comparison is the system layout. The workers have also been considered in the comparison, taking into account their level of efficiency and their position in the assembly system.

The article is structured as follows: the second section presents a brief literature review of the research topic, the third presents the logic of the implemented model and assumptions, the fourth section presents the case study and its results, and some conclusions are given in section 5.

2. Literature review

In the literature, the presence of assembly systems with some kind of parallelisms is not widespread even though implementing parallel assembly lines is beneficial when market demand increases, and the existing system lacks the capacity to handle the growth (Aguilar et al. 2020). In the literature review by Lusa (2008), the author presents all the balancing studies for parallel assembly lines published until 2008, highlighting the pros and cons of implementing this layout. Among the pros, a parallel assembly line leads to better balancing of the system, higher productivity rate, and longer cycle times, which in turn lead to higher workers satisfaction and products quality. One of the disadvantages is that the line will be more expensive to implement. Also in the review of Battaïa and Dolgui (2013) there is a section dedicated to parallel lines, with a particular focus on balancing methods.

There are different ways to implement parallelisms in an assembly system (Boysen et al. 2007) depending on the requirements of the system. Some of the possibilities are the parallelisation of workers, which results in a two-sided or multi-manned assembly line (Kucukkoc and Zhang 2014), the parallelisation of the entire line (Doerr et al. 2000), parallel lines with multi-line workstations (Budak and Chen 2020) or the parallelisation of several or all stations on the line (Lopes et al. 2019, 2018). Focusing on the two configurations analysed in this article, a review of the literature on parallel lines and lines with parallel stations is needed.

The implementation of parallel straight lines has been pursued over the years for different purposes: Süer (1998) suggested using parallel lines to meet the increasing market demand in a single-model production context, Atasagun et al. (2019) proposed to use parallel lines for multi-model production by dedicating each line to a specific product model, and Ahmadi et al. (1992) also considered multi-model production taking into account the setup time between different models. In Tiacci and Mimmi (2018) the ergonomic aspect is integrated into the balancing and sequencing of a straight-line parallel layout to optimise the workload subdivision among workers. In Miqueo et al. (2023) a comparison among three multi-model assembly systems is presented with the aim to identify the more productive system in a high-mix low-volume demand scenario between the fixed worker assembly line (FWAL) and the walking worker assembly line (WWAL) with a single line or with two parallel lines. Their study found that the parallel WWAL has better productivity even though workers cannot change lines or overtake slower workers.

In the case of parallel workstations, Becker and Scholl (2009) present a balancing model for a single-model multi-manned assembly line that can have one or more parallel workstations. In their model, the workers are considered to be equal, and the execution times are deterministic and fixed. Also in (Kellegöz and Toklu 2015) a mathematical model is presented to balance a single-model multi-manned line with parallel workstations. Because the line assembles large products, it is possible to have more than one worker at each workstation, but they are all considered equal. When it comes to mixed-model assembly lines, studies are also often focused on balancing the workload among workstations as seen in McMullena and Frazier (1997). The authors compare different balancing methods to provide production management with a methodology to solve line balancing when task times are stochastic, production is mixed-model, and there are parallel workstations, considering all workers equivalent. Asadi-Zonouz et al. (2020) propose a mathematical method to balance an assembly line with parallel workstations considering the learning effect of the workers and the influence of sequencing on setup times. Finally, Hashemi-Petroodi et al. (2022) present a balancing model based on the dynamic assignment of tasks in a mixed-model assembly line with walking workers in order to minimise both costs and the number of workers while achieving high flexibility and reconfigurability of the system.

The study in the literature that most closely resembles ours is the one of Lopes et al. (2019). The authors present a balancing model to optimise an assembly line with parallel workstations and, in the end, they compare the results with a parallel straight-line system, emphasising that the system with parallel stations offers greater flexibility and productivity. Among their assumptions are a mixed-model production strategy, an unpaced asynchronous assembly line (Boysen et al. 2008), and the possibility for products to change sides of the line (in the system with parallel workstations). They do not take into account worker-dependent time or the possibility of having buffers.

In the context of the present case study, the production strategy employed is multi-model since the batch size is neither unitary nor uniform. However, the setup times required for product changes are not taken into account in this study. Both systems being compared are unpaced asynchronous with buffers, and the analysis also includes the consideration of varying efficiency levels among workers. To the best of the authors' knowledge, there are no similar studies in the literature that address these specific factors in a comparable manner.

3. Layout Description and Model definition

Since the objective is to optimise the productivity of an assembly system, two different layouts have been proposed and analysed using a simulation model built in Anylogic®. The diversity among workers has been considered including their efficiency level in the simulations. Since it is always more difficult to find workers with the right qualifications or to train them properly in short times (Wang et al. 2007, 2005), it is important to evaluate all the possibilities, also because "With an inhomogeneous workforce, the efficiency is also sensitive to worker placement" (Öner-Közen et al. 2017). The main result of the model is the productivity rate of the two systems.

The first system considered is a straight-line parallel assembly system with inter-operational buffers (Figure 1). The presence of two identical parallel lines allows the products to enter the system independently in one or in the other line based on the availability of the first station (stage A). What potentially changes between the correspondent stations is the efficiency level of the workers, but not the task allocation or the tooling.

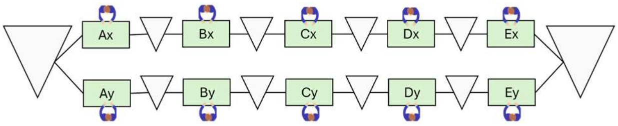

Figure 1: Layout of the two parallel straight-line systems

The second proposed configuration is a fishbone-shaped layout which has a central backbone, with each stage of the line being a branch of it with two sides, each consisting of two workstations handled by a single operator. For each branch, one workstation is always idle, acting like a buffer, while the other is working (Figure 2). The structure is very similar to two parallel assembly lines since there are also two workstations for each stage of the line and the buffers (idle stations). The real difference is that the products have the opportunity to overtake slower products and change sides of the line at any stage if necessary. In this way, there is a constant shuffling of products, which will therefore not leave the line in the same order as they entered it. The workers are simulated with different efficiency levels in order to consider their diversity.

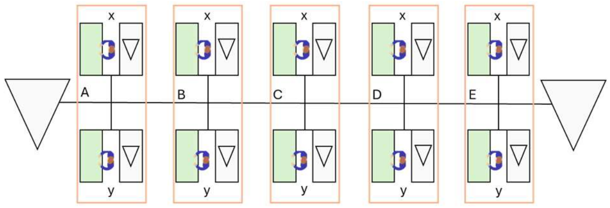

Figure 2: Layout of the fishbone system

Figure 3A shows the logical scheme of the model that manages the two parallel lines, illustrating, for example, the decision process that occurs between two adjacent stages (Z and Z+1) on the x line. The fishbone system has a slightly more complex logical scheme, as visible in Figure 3B.

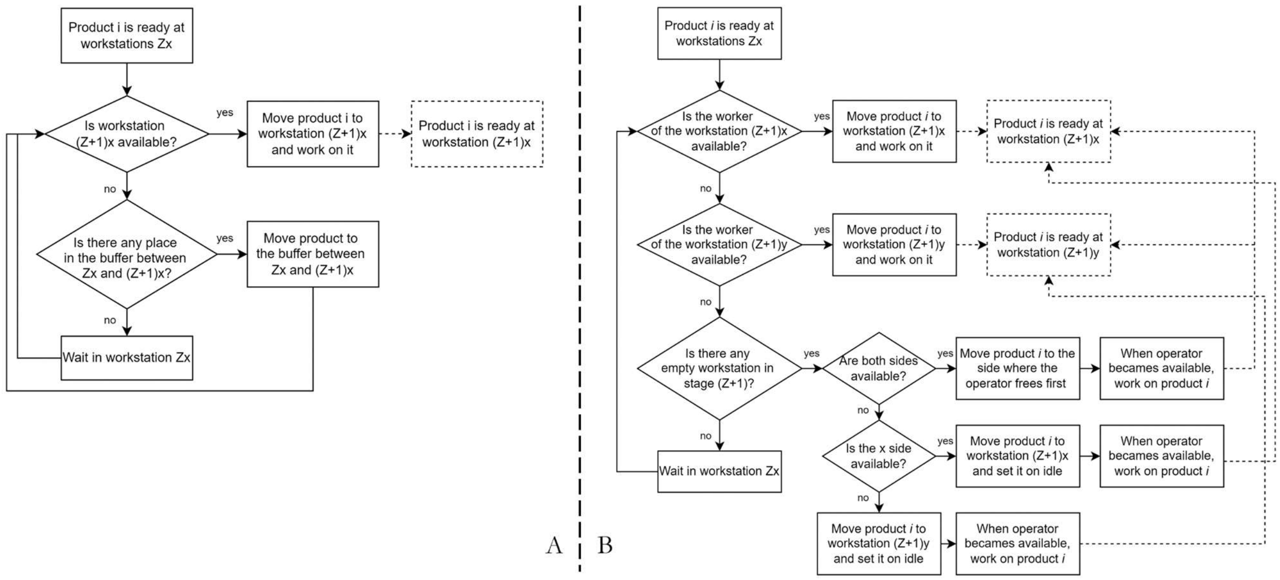

Figure 3: Logical scheme of the parallel straight-line system (A) and of the fishbone system (B)

The assumptions on which the simulations are based are as follows:

- The execution times are deterministic
- The entry sequence of products is the same in both systems
- The parallel straight-line system admits buffers between stations
- The fishbone-shaped layout has an idle station for each workstation in order to emulate the presence of buffers
- In the fishbone line, products can change sides depending on which station is available or which one ends first, so the products can be mixed during the process

- The moving time between workstations is fixed and equal in the two systems
- Each worker can have a different efficiency level, and all possible combinations have been simulated.

4. Case Study

In this study, data from an Italian company that produces air conditioning systems are used as a case study to investigate the effect of layout choice on the productivity rate of a manned assembly system.

The analysed system consists of five manual stages (Ns) and three automated workstations at the end of the process. In order to study only the manual assembly process, the automatic part of the line was not considered. The current layout of the manned workstations, represented in Figure 1, consists of two parallel and identical assembly lines of five workstations in which the stations are rigidly connected by conveyors that also work as buffers. In the actual layout, the conveyor can accommodate only one piece between adjacent stations, so the buffer size in the simulations was also set to one (B_s). Since the goal is to maximise the productivity of the system without altering the distribution of task in the workstations or providing different training for workers, the proposed alternative solution only modifies the structure of connections between stations leading to a fishbone layout. This modification enables the movement of pieces from one side of the central backbone to the other.

In the proposed layout, rather than using buffers between stations, a decoupling station is positioned on each side of every stage of the line to accommodate a small queue of one piece (as seen in Figure 2 in light grey). At each stage of the line there are two operators, one on each side, so the total number of workers (Nw) in the system is 10, as it is in the current layout configuration.

The model described in Section 3 was used to simulate the two assembly systems, with the aim of determining the productivity of each layout with all possible combinations of worker efficiency. The model was executed using authentic production data from a complete year of manufacturing operations. In particular, for each combination of variables, it simulates 6716 products (P_{tot}) without taking into account work shifts, it runs until every product has been simulated. The P_{tot} products are categorised into 18 distinct model groups (P_A-P_R) and within each group, there exists a variable number of sub models, ranging from 2 to 23. Table 1 shows the division into families and the quantity of parts produced for each model. The sum of the red numbers corresponds to the total number of parts processed (P_{tot}) in each simulation. Thus, the production is multi-model with small batches.

Table 1: Product families and pieces produced for each model

P_A		P_B		P_C		P_D		P_E		P_F		P_G		P_H		P_I	
P_A1	2	P_B1	11	P_C1	4	P_D1	19	P_E1	1	P_F1	1	P_G1	55	P_H1	17	P_I1	184
P_A2	8	P_B2	67	P_C2	12	P_D2	103	P_E2	76	P_F2	14	P_G2	129	P_H2	3	P_I2	1
P_A3	38	P_B3	0	P_C3	0	P_D3	18	P_E3	296	P_F3	4	P_G3	1	P_H3	3	P_I3	53
P_A4	36	P_B4	4	P_C4	28	P_D4	1	P_E4	24	P_F4	8	P_G4	52	P_H4	27	P_I4	1
P_A5	2	P_B5	43	P_C5	6	P_D5	34	P_E5	88	P_F5	7	P_G5	187	P_H5	16	P_I5	1
P_A6	1	P_B6	66	P_C6	6	P_D6	171	P_E6	1	P_F6	35	P_G6	124	P_H6	23	P_I6	81
P_A7	7	P_B7	1	P_C7	30	P_D7	18	P_E7	3	P_F7	11	P_G7	1			P_I7	35
P_A8	20	P_B8	6	P_C8	11			P_E8	7			P_G8	223			P_I8	44
P_A9	23	P_B9	61	P_C9	25			P_E9	56			P_G9	1			P_I9	172
P_A10	1	P_B10	1									P_G10	2				
P_A11	6	P_B11	28														
P_A12	16	P_B12	121														
P_A13	6	P_B13	10														
P_A14	74	P_B14	105														
P_A15	2	P_B15	1														
P_A16	36																
P_A17	3																
P_A18	7																
P_A19	2																
P_A20	31																
P_A21	45																
P_A22	8																
P_A23	11																
	385		525		122		364		552		80		775		89		572
P_J		**P_K**		**P_L**		**P_M**		**P_N**		**P_O**		**P_P**		**P_Q**		**P_R**	
P_J1	59	P_K1	9	P_L1	154	P_M1	30	P_N1	143	P_O1	243	P_P1	389	P_Q1	378	P_R1	58
P_J2	144	P_K2	31	P_L2	1	P_M2	2	P_N2	319	P_O2	258	P_P2	4	P_Q2	5	P_R2	187
P_J3	49	P_K3	6	P_L3	15	P_M3	1					P_P3	356			P_R3	15
P_J4	1	P_K4	28	P_L4	55											P_R4	1
P_J5	222	P_K5	33	P_L5	1												
				P_L6	55												
	475		107		281		33		462		501		749		383		261

The imbalance level of the line (Δ_u) is calculated as shown in Equation 1 and is approximately 50%. This value was calculated by knowing the assembly time of each product in each workstation, taking the difference between the maximum assembly time (T_{max}) and the minimum assembly time (T_{min}) of the line, and dividing by the maximum value:

$$\Delta_u = \frac{T_{max} - T_{min}}{T_{max}} \quad (1)$$

When the same evaluation is performed on individual stations, values ranging from 45% to 49% were obtained.

The chosen values to represent the efficiency level (Eff) of the workers are 100% and 70%. Given the large number of operators involved in the line (N_w=10), it was decided to simulate only two efficiency levels, selecting the extreme values from the range found in other literature articles, such as in the one by Al-Zuheri et al. (2016). The total number of combinations tested is 1024, with all possible positions of the 10 workers being simulated. For each combination, the entire production is simulated (P_{tot}). The transportation time between the stations (t_m) is 5 seconds, assuming a conveyor belt speed of 1 m/s and 5 metres between stations. The transportation time (t_m) is assumed to be constant and equal for both systems. However, this choice does not affect the results of the study, as the assembly times at each station are at least three orders of magnitude longer.

The parameters and variables used in the simulations are summarised in Table 2.

Table 2: List of variables and parameters

Variable	**Description**	**Value**	**Unit**
Eff	Efficiency levels	70, 100	%
Parameter	**Description**	**Value**	**Unit**
Ns	Number of stages	5	-
Nw	Number of workers	10	-
Δ_u	Unbalancing level	~50	%
P_{tot}	Total number of products	6176	pcs
t_m	Transportation time	5	s
B_s	Buffer size	1	pcs

As far as the results of the simulations are concerned, it can be said that the convenience of one layout over another is strictly dependent on the efficiency of the operators involved in the system. The relative productivity (RQ%) values of the two modelled systems are obtained as shown in Equation 2 where $Q_{Fishbone}$ is the throughput of the fishbone assembly line and $Q_{Parallel}$ is the throughput of the straight-line parallel assembly system.

$$RQ\% = \frac{Q_{Fishbone} - Q_{Parallel}}{Q_{parallel}} \cdot 100 \quad (2)$$

This calculation was made for each simulation performed, and the results were then averaged, grouping the cases in which two low-efficiency workers were paired at the same assembly stage ($\overline{RQ\%}_0$ no paired stations, $\overline{RQ\%}_1$ one paired station, $\overline{RQ\%}_2$ two paired stations, etc). This distinction has been made because, in the presence of paired workers, the two systems are often equivalent or have little difference in terms of productivity. In fact, the two systems would be equivalent in the case of zero imbalance of the processed family or very large production batches with paired workers, since in these cases there is no advantage in overtaking slower products as the execution time on both sides of the line is the same. The relative productivity value (RQ%) of the fishbone system over the straight-line parallel system ranges from 0.02% when all the operators involved have low efficiency levels, or 0.03% when they have all high efficiency levels, up to approximately 13.5%, as reported in Table 3. The first two columns of Table 3 indicate the number of low- and high-efficiency workers in the simulated system. The subsequent columns show the average of the relative productivity results obtained from each simulation, grouped by the number of paired stations, and the relative standard deviation value (σ_{st}).

Table 3: Summary of the results obtained grouped on the basis of the number of low efficiency workers

70% Eff	**100% Eff**	$\overline{RQ\%}_0$	σ_{st}	$\overline{RQ\%}_1$	σ_{st}	$\overline{RQ\%}_2$	σ_{st}	$\overline{RQ\%}_3$	σ_{st}	$\overline{RQ\%}_4$	σ_{st}	$\overline{RQ\%}_5$	σ_{st}
0	10	0.03	0										
1	9	3.07	0.93										
2	8	6.89	5.19	0.05	0.10								
3	7	9.25	4.81	1.31	0.78								
4	6	10.58	3.88	2.28	1.18	0.03	0.07						
5	5	11.19	2.96	3.06	1.40	0.68	0.49						
6	4			3.68	1.51	1.24	0.74	0.04	0.05				
7	3					1.73	0.87	0.48	0.27				
8	2							0.90	0.37	0.03	0.04		
9	1									0.42	0.24		
10	0											0.02	0

In the presence of mismatched operators, the fishbone system offers greater convenience, as parts can pass to the other side of the line and continue on their way when encountering a slower worker, unlike in the parallel straight-line system where they have to wait for the next stage to become available.

What emerges from this study is that the presence of inefficient workers in the system increases the feasibility of implementing a fishbone system, as long as they can be placed in the system without corresponding inefficient operators; that is, when they are fewer in number or equal to the total number of stages in the system. In the considered case study, they must be fewer in number or equal to 5 to achieve a greater advantage.

Another interesting result is that implementing a fishbone is more suitable when the assembly process is in unit batches (mixed-model strategy). In fact, even in the presence of paired workers, there is always the possibility of having a product on one side of the line that has a different assembly time and therefore the possibility to change sides of the line can be exploited.

The productivity values decrease in absolute terms in presence of inefficient operators. However, as it becomes increasingly challenging to find efficient or well-trained workers (Wang et al., 2007), it becomes necessary to consider such factors when designing an assembly system, especially in the case of manned systems.

5. Conclusion and future research

In the case study analysed in this article, the objective was to compare the productivity results of two different assembly system layouts without changing the balancing of the system. The two compared layouts were the two parallel straight-line layout and the fishbone layout (assembly line with parallel workstations). The comparison was carried out by simulating all possible positions of 10 operators with two possible efficiency levels each, to determine the most advantageous position for placing the less efficient operators. The equivalent of one year's production was simulated for each combination.

From the study emerges that in the presence of homogeneous operators, the two systems are approximately equivalent in terms of productivity rate, with a slight advantage for the fishbone layout. However, this small advantage does not justify changing the layout itself. When operators are mixed in terms of efficiency, the advantage of the fishbone layout particularly increases when the number of paired stations is minimal. This happens because the two systems become more similar when the number of stages with two workers with the same efficiency level (paired stations) increases and there are less opportunities for parts to switch side of the line. It can also be shown that the greatest advantage of the fishbone layout is in the case of unit production batches, as the possibility of having the same assembly time on both sides of the line is minimised and the possibility of interchange is favoured.

This study has a major limitation in that it is based on a single case study but there are several possibilities of future research that could stem from this study.

It can be extended to become a parametric study in which each parameter, considered here as fixed, could be analysed more broadly to examine how each one affects the final productivity of the system. Moreover, including economic aspects in the evaluation could be interesting in determining how long it takes for the implementation of the fishbone system to pay for itself in terms of productivity gains, if at all.

It is also possible to consider a flexible transport system between stations for the fishbone assembly line, implemented through a fleet of Autonomous Mobile Robots (AMRs). This approach may require less investment than a rigid transport system such as a linear or a fishbone-shaped conveyor. Such a flexible transport system would provide not only the possibility to change sides of the line but also to backtrack, if necessary. Furthermore, the number of AMRs could be adjusted according to the volume of market demand, which is a great advantage, as the market is constantly and rapidly changing.

Another promising direction for future research is the creation of a mathematical model to optimise both system balancing and operator allocation. This study would be particularly valuable, as the current literature lacks proposals for balancing asynchronous assembly systems with parallel stations and buffers while also considering worker allocation.

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