Basic Layouts for Modular Assembly Systems – a Simulation-based Comparison

Soeren Bergmann*, Steven Ehrle

Group for Information Technology in Production and Logistics, Ilmenau University of Technology, Max-Planck-Ring 12, 98693 Ilmenau, Germany; **soeren.bergmann@tu-ilmenau.de*

SNE 34(2), 2024, 101-110, DOI: 10.11128/sne.34.tn.10686
Selected ASIM SPL 2023 Postconf. Publication: 2023-09-01;
Received Revised Improved: 2024-04-22; Accepted: 2024-05-10
SNE - Simulation Notes Europe, ARGESIM Publisher Vienna
ISSN Print 2305-9974, Online 2306-0271, www.sne-journal.org

Abstract. The article discusses the challenges posed by increased individualization of products, shorter product life cycles, and external factors on the flexibility of modern production systems.
In particular, flexible workshop-oriented manufacturing principles are being implemented to replace or supplement traditional assembly lines, with various terms such as "modular assembly" and "matrix production" etc. used to describe similar concepts. The article presents these concepts under the umbrella term of modular production or assembly systems, which utilize adaptable workstations and autonomous vehicles to transport production orders between stations.
The design of such systems is crucial to their performance, with considerations such as task allocation, material supply, and fleet sizing requiring complex interplay. The article compares traditional matrix layouts with alternative options, such as single-lane pathways and non-matrix layouts like honeycomb or star shapes, using simulation-based analysis to evaluate their potential impact on system performance.

Introduction

New challenges based on increased individualization of products, shorter product life cycles, external influences, etc. [18] lead to increased requirements regarding the flexibility of modern production systems. Final assembly in particular must be able to react flexibly to changing conditions and requirements without neglecting the economic efficiency of product assembly or the various product variants [7, 8, 22].

One of the main planning problems here is that the individual tasks (process steps) can be very different, and it is therefore almost impossible to define a uniform system cycle time, see Figure 1. Furthermore, it is increasingly desirable to realize changes in the production system without or at least with very little interruption to the production process.

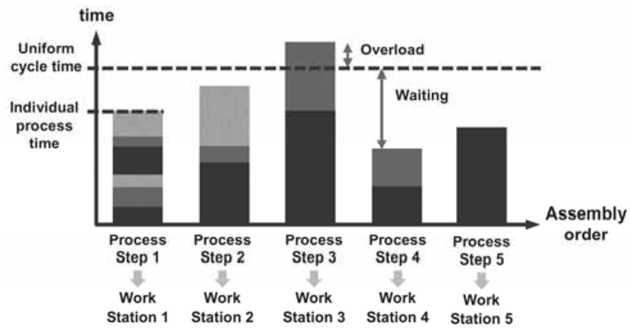

Figure 1: Individual process times vs. uniform cycle time [13].

Traditional flow shop/line production sometimes reaches its limits and is replaced or supplemented by more flexible, workshop-oriented production principles.

A number of pilot projects can be observed in the automotive industry in particular [12], in which different players describe similar concepts using different terms that sometimes only differ in detail. For example, terms such as "modular assembly" [1, 15], "Flexi-Line" [19], "fully flexible factory" [6], or "matrix production" [13] can be found in the literature.

The common goal of all these approaches is to manufacture several product types or their variants efficiently in the same production facility and, in the best case, to avoid lengthy conversions or new builds when introducing new products. In the best-case scenario, new products can even be introduced without interrupting ongoing operations [10]. In this article, these concepts are subsumed under the collective term modular production or assembly systems.

Such modular production or assembly systems consist of adaptable workstations (production cells) with their specific tools and trained personnel, at which one or usually several different production or assembly activities (tasks) can be carried out. The production orders, in the case of final car assembly the car bodies, are transported using automated guided vehicles (AGVs). The specific routing is determined ad hoc by the system, taking into account the existing technical restrictions and the individual task packages of the products or product variants to be manufactured as well as the current status of the overall system [8, 14].

According to Kern [15], the main features of modular assembly systems can be summarized as follows:

- Decoupled stations, in particular the elimination of cycles and assembly lines,
- self-control, both at the level of orders and of all resources,
- integrated processes, particularly with regard to logistics, material provision and quality management, and
- the ability to adapt to changing requirements over time.

The most obvious initial challenge is the operational control of such systems. For example, various levels must be considered when controlling the AGVs alone [8, 9], see Figure 2.

Furthermore, the material supply of the production cells is also a non-trivial task with very specific additional requirements.

In addition to the control system, the system design is crucial for the performance of the entire production system. When designing a modular production system, various design dimensions, which are already complex in themselves, must be considered in their interactions. For example, the allocation of activities/skills to production cells, i.e. which production steps are possible on which production cells, is a crucial point [2, 3]. The design and dimensioning of the AGV fleet, the number and training of workers and much more must also be considered.

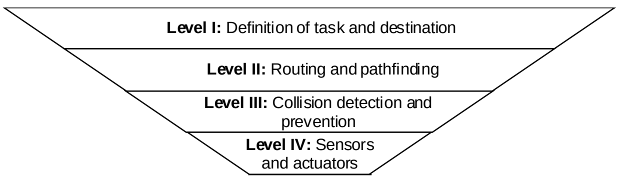

Figure 2: Hierarchy of decision-making [9].

In the vast majority of cases, the production cells have so far been positioned in a chessboard/matrix arrangement with often complete two-lane path systems in the hall layout [13]. This article will use a simulation-based comparison to investigate whether there is general potential for improvement here or whether other equivalent or even better alternatives are conceivable. On the one hand, deviating path topologies for matrix layouts, e.g. single-lane paths or incomplete path networks, will be examined. On the other hand, deviating basic layouts, e.g. an arrangement of the production cell in the form of honeycombs/hexagonal or in a star layout, will be examined. In particular, the achievable system performance (throughput, workloads, etc.) as well as the utilization of the routes, the congestion behaviour of the AGVs or the space requirements of the route network, among other things, must be examined.

In addition, the interaction between the layout and the allocation of activities/skills to production cells will be shown using an initial small test setup.

The article, which is an extended version of the article published at ASIM Dedicated Conference 2023 [4], is structured as follows: The introduction introduces the topic of the article and clarifies the motivation. This is followed by a brief description of the current state of research and the necessary theoretical foundations on the subject of modular production systems, in particular their layout. Building on this, the main part of the article first presents a basic comparative scenario of realistic modular production as well as various layout variants. Where necessary, assumptions and restrictions are discussed. Furthermore, the results of initial simulation experiments on the individual layout variants are briefly presented, as well as a short excursus on the effects of different allocation of activities/skills to production cells. A critical assessment and an attempt to generalize the findings are also made. The article closes with a conclusion and an outlook on further interesting research opportunities in the context of modular production.

1 Layouts of Modular Assembly Systems

In modular assembly systems, which are largely used synonymously for a number of similar terms in this article, the principle of flow production that has often prevailed in final assembly to date is replaced by a more workshop-oriented assembly.

Such systems can often also be understood as cyber-physical systems, whereby the use of data, e.g. sensor data and automated transport systems, enables a certain degree of decentralized autonomous control that can react to the individual situation of the assembly system at any time [5, 15, 16].

Such systems are characterized in particular by

- decoupled workstations (production cells) with individual cycle times,
- several activities / skills per production cell,
- redundancies of skills on different production cells and
- flexible material flows by means of AGVs (automated guided vehicles).

When designing modular assembly systems, various design dimensions must be taken into account, which often interact with each other. These include

- the assignment of activities/skills to production cells [3],
- the design of the control of production orders including AGVs [10],
- the planning of material supply [11] and
- the distribution and arrangement of the production cells (layout).

This article focuses on the influence of layout on the performance of modular assembly systems, although there are significant interactions with other design dimensions, e.g. in the allocation of activities/skills to production cells, control strategies, etc.

In the following, layout is understood as the result of layout planning, i.e. the (often graphical) spatial arrangement of the structural and functional elements relevant to production [17, 20]. One subtask is the planning of transport routes and material flows, which has a significant influence on system performance [20]. As flexible transportation systems such as AGVs are used in modular assembly systems, the route network and buffers, both at production cells and in the warehouse etc., are particularly relevant.

Currently, matrix or chessboard-like arrangements are common in the mostly rectangular halls, in which complete two-lane road networks that can be driven on in both directions usually predominate [10, 21].

To evaluate the performance of modular assembly systems, the broad portfolio of key figures from the context of factory planning [20] can be used.

In the following, static indicators such as the required space, the total length of the route network and the proportion of routes in the total area are calculated and indicators such as the throughput, the average throughput time per product type, the average travel distance/travel time per product and the utilization of the routes are determined by means of simulation experiments.

2 Simulation-based Comparison of Basic Layouts Using a Case Study

Before, as promised, various alternative layouts with the corresponding route networks are considered, a scenario for a modular assembly system will first be introduced. The scenario is designed in such a way that it is sufficiently complex and takes into account many factors known from practice. At the same time, it is explainable and can be described within the scope of the article.

The following assumptions and characteristics are used as a basis: the area available for modular assembly is max. 80x70m, 16 possible production cells (each with its own buffer area for 3 AGVs) are planned. Production cells take up approx. 11x11m of hall space. Lanes require a minimum width of 2m per lane.

production cell no	assigned activities
I	A, B, H
II	C, D, E
III	A, B, H
IV	C, D, E
V	J, F
VI	J, F
VII	G, I
VIII	G, I
IX	R, S, T
X	R, S, T
XI	K, M, P
XII	K, M, P
XIII	O, L
XIV	O, L
XV	N, Q
XVI	N, Q

Table 1: basic scenario assignment of activities to production cells.

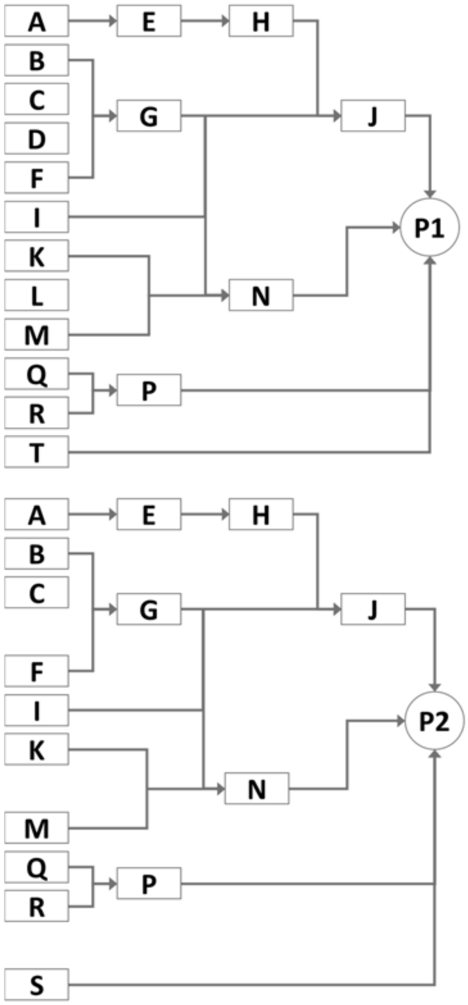

Figure 3: Priority graphs for product 1 (top) and product 2 (bottom).

The assignment of activities to production cells (see Table 1) was defined in advance and is comparable for all basic scenarios. Alternative assignments are introduced in the explanations of the effects of the assignment in interaction with the layouts.

Basically, between two and three different activities/assembly steps are assigned to each production cell. In addition, two product types were defined that occur with equal frequency. Each product type has up to 18 production steps and has its own priority graph (see Figure 3) as well as individual processing times.

AGV control is decentralised and rule-based. Specifically, from the possible production cell, which depend on the currently possible assembly steps, the AGVs select the one with the shortest queue or the one that is not yet occupied.

In the event of a tie between several cells, the closest cell is approached. If this is also not clear, a random choice is made.

The selection of the control method influences the performance of the modular production system and it can also be assumed that there is an interaction between the control and the layout, which is neglected in the following explanations.

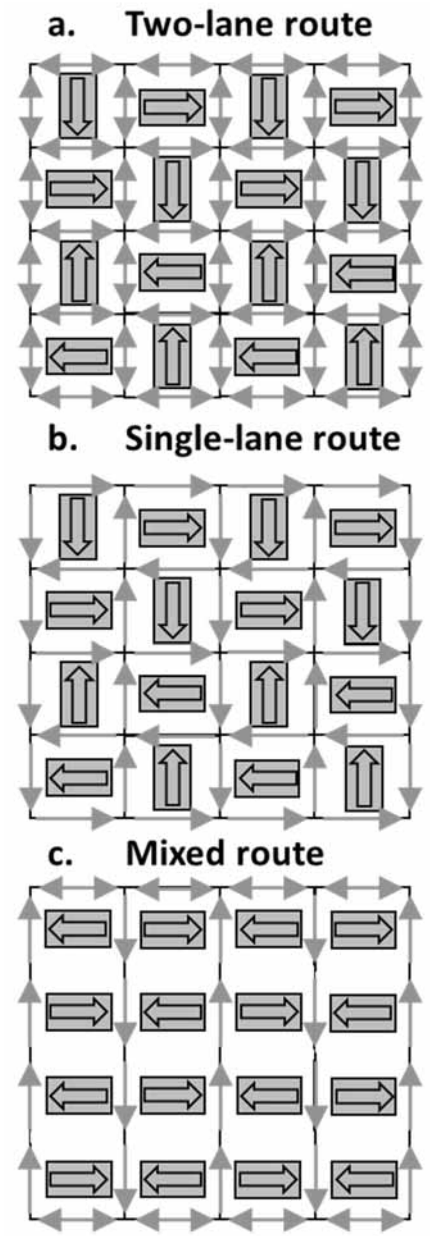

Figure 4: Three variants of matrix layouts.

Furthermore, the number of AGVs and thus the number of orders active in the system at the same time was set to 22 based on preliminary experiments. For the material supply, shopping baskets are assumed which are on the respective AGVs from the outset. This means that an explicit mapping of the material supply can initially be abstracted. The simulation time in the Siemens Plant Simulation simulator was 144 hours (6 days) per experiment run.

In addition to the classic matrix arrangement already mentioned (Figure 4, top) with a complete two-lane route system, 6 other layouts or route network variants were compared (see Figure 4, Figure 5, and Figure 6). It should be noted that the idea of a free arrangement of stations without fixed routes was initially rejected for this comparison due to the lack of comparability.

In addition to the obvious visual differences between the basic variants matrix layout (see Figure 4), honeycomb/hexagonal layout (see Figure 5), and star layout (see Figure 6), the detailed design of the road networks is of particular interest. For all two-lane road systems, it is assumed that all roads have two lanes and are therefore 4 meters wide. This not only enables overtaking, but also allows AGVs to meet on one section of the route. In contrast, all single-lane path systems are assumed to be one-way streets in order to avoid deadlocks. It is essential to ensure that there are no dead ends.

The two variants referred to as "mixed road systems" are special cases in which both two-lane and single-lane roads are present in the road network. In the mixed matrix arrangement, the paths at the top and bottom are two-lane, while all vertical paths in the illustration are single-lane. The direction of the single-lane paths is alternating. In the star-flow arrangement, single and double-track paths are also used in the mixed path system. In concrete terms, the inner ring is a one-lane road and therefore one-way.

layout	Total length / width	Base area [m²]	Path area [m²]
Matrix 2-lane	64m / 64m	4.096	2.146
Matrix 1-lane	54m / 54m	2.916	977
Matrix mix	58m / 55m	3.190	902
Hex 2-lane	80m / 68,5m	4.385	2.221
Hex 1-lane	68m / 58,5m	3.318	1.017
Star 2-lane	62m / 62m	2.907	647
Star mix	62m / 62m	2.907	499

Table 2: Area comparison of the implemented layout and route network variants.

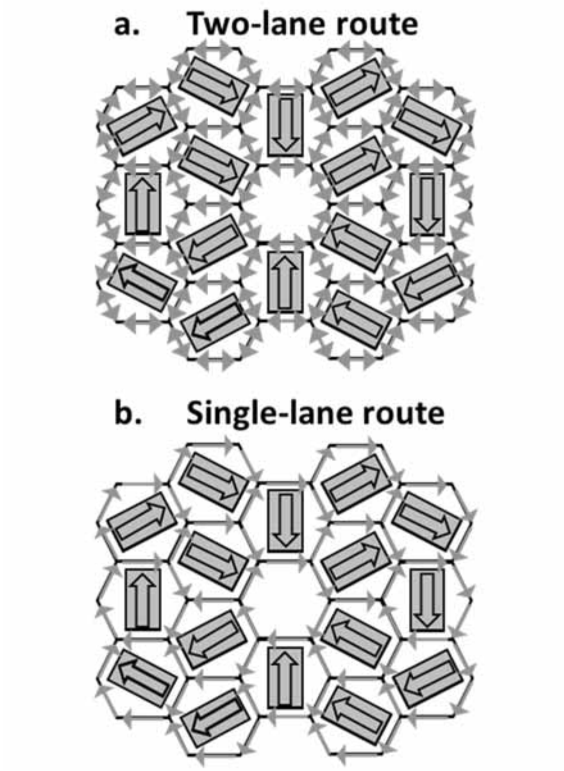

Figure 5: Two variants of honeycomb/hexagonal layouts.

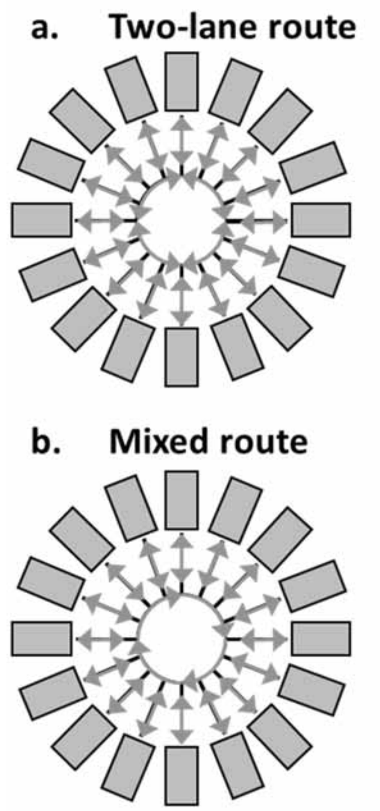

Figure 6: Two variants of a star layout.

As already mentioned, initial key performance indicators for the individual layouts can already be calculated without simulation experiments. The required area and the proportion of paths in the total area differ considerably in some cases (see Table 2).

It is clear to see that the star layout, which at first glance appears quite unusual, has the smallest area requirement in this scenario, whereby the free space created in the interior has been deducted here. However, the practical scalability of this layout to more stations is doubtful. It can also be seen that single-lane routes generally require less space and that the honeycomb / hexagonal layouts require a slightly larger area overall than the classic matrix layout. But, it should be noted that the honeycomb/hexagonal layouts have negative edge surfaces (half hexagons) and that one hexagonal remains completely free. These free areas could possibly be used for other purposes in practice. It can also be assumed that there is further potential for saving space with non-rectangular production cells, ideally also designed as hexagons.

Using simulation, a screenshot of the model for the honeycomb layout is shown in Figure 7, further parameters were determined for all 7 variants; the throughput, the average travel distance per product and the average travel time per product can be seen in Table 3. These comparative values also show clear differences.

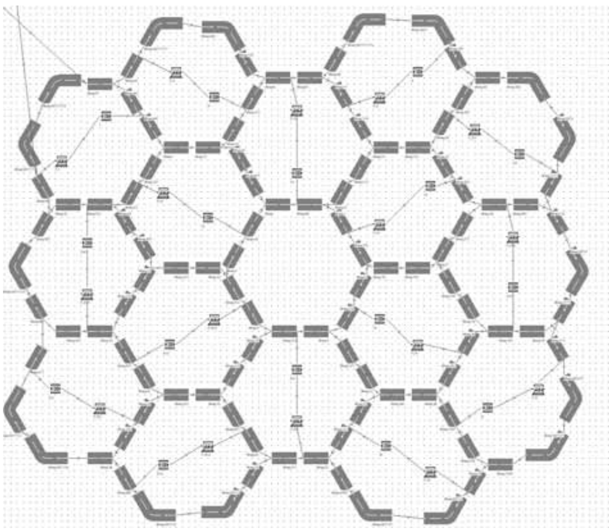

Figure 7: Screenshot of the simulation model for the honeycomb/hexagonal layout in the simulator Siemens Plant Simulation.

layout	Through put [pcs.]	Avg. route length [m]	Avg. movement time [min]
Matrix 2-lane	170	699,85	11,5
Matrix 1-lane	161	1.592,11	26,5
Matrix mix	171	1.482,82	24,5
Hex 2-lane	171	771,12	13,0
Hex 1-lane	170	1.381,15	23,0
Star 2-lane	112	605,04	10,0
Star mix	116	970,47	16,0

Table 3: Comparison of throughput, average route length, and movement time of the layout variants.

A significantly lower throughput can be observed for both star-shaped layouts, as blockages occurred in the simulations that led to a complete standstill in production. The single-lane matrix layout also achieves slightly lower throughput values, as the AGVs occasionally have to wait in front of full buffers, which are then difficult to avoid. Improved control of the AGVs or mechanisms to prevent and eliminate blockages could possibly counteract this problem.

Such effects do not occur with two-lane matrix or honeycomb/hexagonal layouts, as the lanes are not completely blocked and overtaking are possible. With the mixed matrix layout, the possibility of overtaking on the two-lane paths is obviously sufficient to avoid negative effects. The single-lane honeycomb/hexagonal layout shows surprising behaviour, with hardly any blockages occurring despite the lack of overtaking opportunities. This is due to the fact that there are often very good alternative routes between two points. The fact that there are no junctions with four entrances or exits also has a positive effect, which significantly reduces the complexity in the event of a conflict.

In general, however, it can be seen that transportation times do not immediately affect throughput and should therefore not be the main criterion for planning. In contrast, the occurrence of blockages is an important factor that must be taken into account during planning.

In order to provide further insights, the last parameter presented here is the utilization of the routes. The analysis of the utilization of the routes, based on the number of trips per route segment, provides further insights into the system. In order to make the utilization of the routes more comparable, all route segments or subsections were divided into one of four classes.

The classification is based on the number of journeys made on the respective route segments. These classes serve to better differentiate the utilization and allow a comparison of the routes so that bottlenecks and congestion can be identified. The classes are as follows: Green 0-499 travel orders (very low utilization), Yellow 450-899 travel orders (medium utilization), Orange 900-1349 travel orders (high utilization), and Red 1350-1800 travel orders (very high utilization). Table 4 shows the results of this analysis.

It can be seen that in the two-lane matrix and honeycomb/hexagonal layouts, the utilization of the routes is lower overall, as vehicles have the opportunity to overtake and/or use alternative routes. The utilization values tend to be higher for the single-lane routes, as there are no overtaking opportunities and vehicles may have to wait. Interestingly, the star-shaped layouts have lower utilization values, despite the blockages and lower throughput.

This is because the routes inside the star, where the blockages occur, have fewer trips due to the production standstill. The routes outside the star, on the other hand, are relatively free and therefore have lower utilization values.

With single-lane or mixed matrix layouts, on the other hand, a small number of the routes are used much more frequently (orange and red). It can be assumed that this effect can possibly be reduced, but probably not completely eliminated, by adjusting the distribution of activities on the production cells or optimizing the AGV control strategies.

With single-lane or mixed matrix layouts, on the other hand, a small number of the routes are used much more frequently (orange and red).

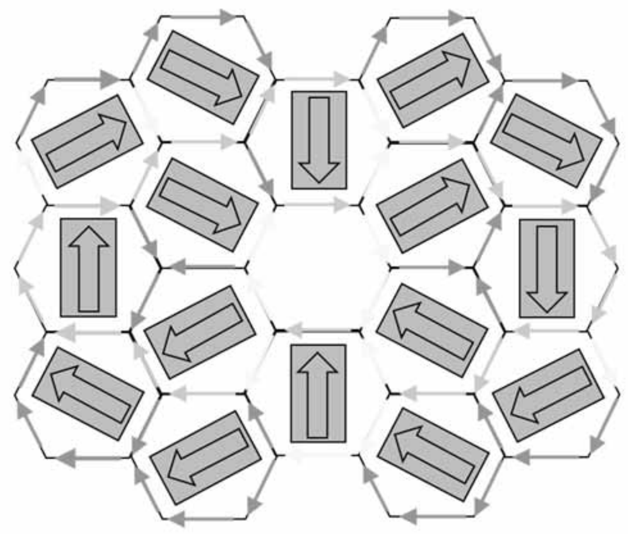

Figure 8: Visualization of the utilization of the routes for the single-lane honeycomb/hexagonal layout.

It can be assumed that this effect can possibly be reduced, but probably not completely eliminated, by adjusting the distribution of activities on the production cells or optimizing the AGV control strategies.

Again, the single-lane honeycomb/hexagonal layout proves to be surprisingly robust in the test, in which some routes have a higher utilization than in the two-lane case, but no very highly utilized routes (red) occur. The visualization of the path utilization, as shown in Figure 8 for the single-lane version, can provide additional insights into problematic areas of the modular assembly system.

The experiments conducted so far do not provide any definitive and generally valid results regarding the advantages of a specific layout for any modular assembly system.

layout	**Number of route segments per class**				**Total number of path segments**
	Green (0-449)	**Yellow** (450-899)	**Orange** (900-1349)	**Red** (1350-1800)	
Matrix 2-lane	85	13	0	0	98
Matrix 1-lane	58	28	16	17	119
Matrix mix	25	25	26	10	86
Hex 2-lane	94	20	0	0	114
Hex 1-lane	56	28	30	0	114
Star 2-lane	16	16	0	0	32
Star mix	13	3	0	16	32

Table 4: Utilization of the route system of the implemented layout variants.

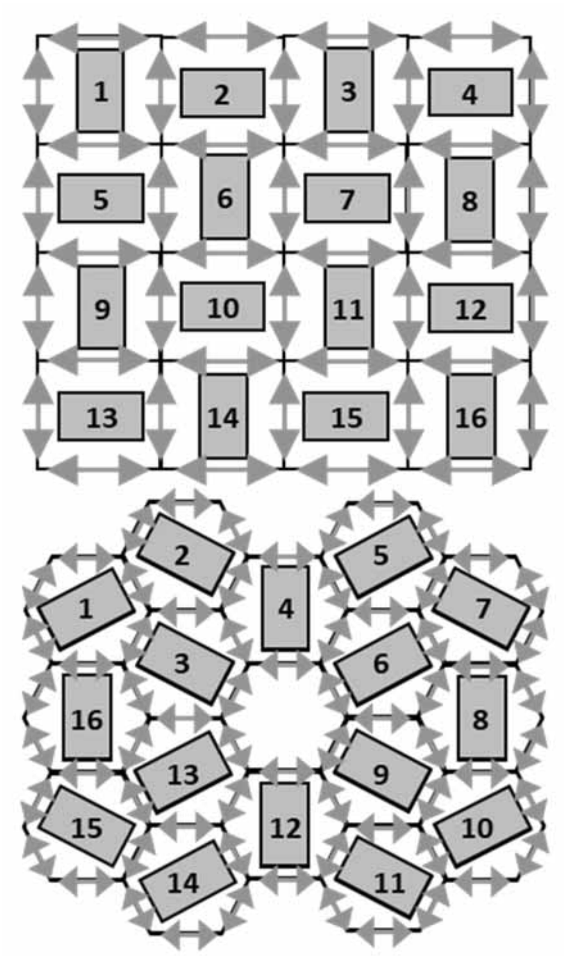

Figure 9: Cell Position in the matrix layout (top) and the honeycomb/hexagonal layout (bottom).

Nevertheless, it can already be summarized that the layout apart from the classic matrix arrangement represents a previously underestimated design factor. The single-track honeycomb/hexagonal layout in particular shows potential in the results presented. They offer a good compromise between system performance and space requirements.

If edge areas (half honeycombs) can be used sensibly and the production cells are not restricted to rectangular layouts, but can ideally be designed in the form of hexagons, the honeycomb/hexagonal layout could represent a serious alternative to classic matrix layouts.

On the other hand, layouts that tend to block, such as star layouts, are not suitable. If such layouts are chosen, it is essential to implement mechanisms to prevent and eliminate blockages.

Short Excursus on the Effects of Different Allocation of Activities/Skills to Production Cells

As already mentioned, it can be assumed that there are dependencies between the design dimensions of modular production systems, so that it is relatively obvious to assume interactions between the assignment of tasks to production cells and the layout.

The following is not a comprehensive study on this topic, but the interactions are shown and qualitatively evaluated in a rather small-scale experimental setup.

Therefore, only two layouts are considered for the following analyses: the two-lane matrix layout and the two-lane honeycomb layout (Figure 9). In order to minimize the direct effects of activity allocation, which have been shown to be very significant (see [3]), no changes are made to the combinations of activities on the cells in the experiments. For example, there are always two cells (I and III) in the system that have the combination of activities A, B, H. All 16 combinations can be looked up in Table 1.

In the experiment, only the positions/station numbers are varied, e.g. in the first experiment the positions of production cell I and V, II and VI etc. are swapped. A total of 5 variants were simulated in both layouts, see Table 5.

Position in the layout	production cell in variant:				
	1 (base)	2	3	4	5
1	I	V	II	IV	VIII
2	II	VI	I	III	IX
3	III	VII	IV	II	III
4	IV	VIII	III	I	XIII
5	V	I	VI	VIII	VI
6	VI	II	V	VII	XI
7	VII	III	VIII	VI	XV
8	VIII	IV	VII	V	II
9	IX	XIII	X	XII	XII
10	X	XIV	IX	XI	V
11	XI	XV	XII	X	VII
12	XII	XVI	XI	IX	XIV
13	XIII	IX	XIV	XVI	I
14	XIV	X	XIII	XV	X
15	XV	XI	XVI	XIV	XVI
16	XVI	XII	XV	XIII	IV

Table 5: Cell positioning variants.

The analysis of the simulation data showed that, at least in this case study and the selected cell positioning variants, there was hardly any influence on throughput, station utilization, etc. For example, the throughput in the experiments deviated upwards or downwards by less than 1%.

Only the utilization of individual routes changed, whereby here too there were no critical (red) loads on routes in any variant, but rather moderate shifts in the loads on routes. Only the matrix layout in variant 5 resulted in a high but not yet critical load on the central intersection, which was already over-utilized in all scenarios. Otherwise, the class distribution compared to the basic variant (see Table 4) was almost identical for all variants.

In summary, it can be said that interactions were shown to be weaker than initially expected; further investigations in other layouts and in combination with different ability distributions seem advisable.

3 Conclusion and Outlook

In this article, a simulation-based comparison of different layouts and route network topologies for modular assembly was carried out. A fictitious scenario was used, and although the results are certainly not universally valid, it was at least possible to show the potential of non-classical matrix arrangements and the influence of the design of the route networks.

Further considerations on layouts and route network topologies for modular assembly systems are certainly appropriate. Several limitations were encountered in our analysis. On one hand, not all possible variants were considered; for example, freely positioned production cells without an explicit route network were excluded due to a lack of direct comparability. On the other hand, further investigations are necessary. Ideally, these would involve real-world scenarios to enable more generally valid conclusions.

Furthermore, some points are still need additional research. For example, the supply of materials for modular assembly systems has hardly been investigated to date. The article assumed a supply with a shopping basket, which is not always possible in practice. However, other material supply concepts may lead to additional traffic on the routes and thus to a considerable increase in the load on these routes, which may increase the risk of blockages, etc.

Furthermore, despite individual publications on this topic, there is still considerable potential for research into the control of modular assembly systems.

Finally, a transition from partial considerations to holistic approaches will be necessary in the medium term because, for example, as indicated here, decisions such as the assignment of tasks to workstations are closely linked to layout design, material supply and control. The excursus on selecting the station positioning could provide a small insight here.

However, mastering the complexity of such comprehensive approaches represents a major challenge.

Furthermore, fundamental research topics from the world of simulation are also relevant here. On the one hand, AI and simulation is an exciting subject area, where a wide variety of approaches are conceivable, e.g. for system control or system design, but also for analyzing experiments or communicating the results.

On the other hand, automation and support for model generation continue to be an issue; in addition to classic data-driven approaches, AI-based methods can also help to achieve good simulation models more quickly.

References

[1] Audi AG. *Die Modulare Montage - Fertigungsinseln statt Fließband*. 2019. https://www.audi-illustrated.com/de/smart-factory/Die-Modulare-Montage. Accessed 28 January 2022.

[2] Bergmann S. Optimierung des Designs modularer Montagesysteme. In *ASIM SST 2022 Proceedings Langbeiträge. 26. ASIM Symposium Simulationstechnik, 25.07.-27.07.2022, TU Wien*. ASIM Mitteilung 180. ARGESIM Verlag, Wien, 15–22. DOI 10.11128/arep.20.a2006

[3] Bergmann S. Optimization of the Design of Modular Production Systems. In *Proceedings of the 2022 Winter Simulation Conference*. IEEE, 1783–1793, 2022. DOI 10.1109/WSC57314.2022.10015350

Bergmann S, Ehrle S. Grundlayouts für modulare Montagesysteme – ein simulationsbasierter Vergleich. In *Simulation in Produktion und Logistik 2023*. ASIM-Mitteilung Nr. 187, 2023. Universitätsverlag Ilmenau, Ilmenau, 197–206. DOI 10.22032/DBT.57809

[4] Burggräf P, Dannapfel HM, Adlon T, Schukat E, Kahmann H, Holtwiesche L. Modeling and evaluating agile assembly systems using mixed-integer linear programming. In *Proceeding of the 53rd CIRP Conference on Manufacturing Systems 2020*, 1073–1078. DOI 10.18154/RWTH-2021-06580.

[5] Daimler AG. *Factory 56 – Mercedes-Benz Cars Increases Flexibility and Efficiency in Operations.* 2018. https://www.daimler.com/innovation/production/factory-56.html.

[6] El Maraghy H, Schuh G, ElMaraghy W, Piller F, Schönsleben P, Tseng M, Bernard A. Product variety management. 2013. *CIRP Annals* 62, 2, 629–652.

[7] Feldkamp N, Bergmann S, Strassburger S. Modelling and Simulation of Modular Production Systems. 2019. In *Simulation in Produktion und Logistik 2019*, M. Putz and A. Schlegel, Eds. Verlag Wissenschaftliche Scripten, Auerbach, 391–401.

[8] Feldkamp N, Bergmann S, Strassburger S. Simulation-Based Deep Reinforcement Learning for Modular Production Systems. In *Proceedings of the 2020 Winter Simulation Conference*. Institute of Electrical and Electronics Engineers, Piscataway, New Jersey, 1596–1607.

[9] Feldkamp N, Bergmann S, Straßburger S. Simulations-basiertes Deep Reinforcement Learning für Modulare Produktionssysteme. In *ASIM SST 2022 Proceedings Langbeiträge. 26. ASIM Symposium Simulationstechnik, 25.07.-27.07.2022, TU Wien*. ASIM Mitteilung 180. ARGESIM Verlag, Wien, 65–72. DOI 10.11128/arep.20.a2007

[10] Fries C, Wiendahl HH, Assadi AA. Design concept for the intralogistics material supply in matrix productions. In *Proceedings of the 30th CIRP Design 2020. CIRP Design 2020*, K. Mpofu and P. Butala, Eds. Procedia CIRP 91. Elsevier, 33–38. DOI=10.1016/j.procir.2020.02.147

[11] Göppert A, Hüttemann G, Jung S, Grunert D, Schmitt R. Frei verkettete Montagesysteme. 2018. *ZWF* 113, 3, 151–155.

[12] Greschke P, Schönemann M, Thiede S, Herrmann C. Matrix Structures for High Volumes and Flexibility in Production Systems. 2014. *Procedia 5CIRP6* 17, 160–165.

[13] Hüttemann G, Gaffry C, Schmitt RH. Adaptation of Reconfigurable Manufacturing Systems for Industrial Assembly – Review of Flexibility Paradigms, Concepts, and Outlook. 2016. *Procedia 5CIRP6* 52, 112–117.

[14] Kern W. *Modulare Produktion: Methodik zur Gestaltung eines modularen Montagesystems für die variantenreiche Serienmontage im Automobilbau.* 2021. Springer Fachmedien, Wiesbaden.

[15] Kern W, Bauernhansl T. Types and Usage of Assembly Priority Charts in a Modular Assembly System. In *24th International Conference on Production Research (ICPR 2017).* Curran Associates, Inc., 2020, Red Hook, NY.

[16] Kikolski M, Ko CH. Facility layout design – review of current research directions. *Engineering Management in Production and Services* 10, 3, 70–79, 2018.

[17] Koren Y. *The Global Manufacturing Revolution. Product-Process-Business Integration and Reconfigurable Systems*. Wiley Series in Systems Engineering and Management 1. John Wiley & Sons, New York, NY, 2010.

[18] Mayer B. *Ich bin ein Fan von Effizienz*. 2018. https://www.automobil-produktion.de/interviews-734/porsche-produktionsvorstand-reimold-wir-ziehen-alle-register-126.html?page=4. Accessed 8 May 2023.

[19] Schenk M, Wirth S, Müller E. *Fabrikplanung und Fabrikbetrieb. Methoden für die wandlungsfähige, vernetzte und ressourceneffiziente Fabrik.* 2014. VDI-Buch. Springer Berlin Heidelberg, Berlin, Heidelberg.

[20] Schönemann M, Herrmann C, Greschke P, Thiede S. Simulation of Matrix-Structured Manufacturing Systems. 2015. *Journal of Manufacturing Systems* 37, 1, 104–112.

[21] Spath D. Ed. 2013. *Produktionsarbeit der Zukunft - Industrie 4.0*. Fraunhofer-Verl., Stuttgart.