DOI: 10.2507/37th.daaam.proceedings.xxx

INTEGRATED RATIONALISATION OF LAYOUT AND COMPONENT PREPARATION IN HIGH-VARIETY MAKE-TO-ORDER PRODUCTION

Tomáš Broum, Fidan Ferizi & Štěpán Hlaváček

This Publication has to be referred as: Broum, T[omas]; Ferizi, F[idan] & Hlavacek, S[tepan] (2026). Integrated Rationalisation of Layout and Component Preparation in High-Variety Make-To-Order Production, Proceedings of the 37th DAAAM International Symposium, pp.xxxx-xxxx, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-xx-x, ISSN 1726-9679, Vienna, Austria
DOI: 10.2507/37th.daaam.proceedings.xxx

Abstract

This paper presents a design-oriented case study of production system rationalisation at an anonymised industrial enterprise. The study addresses high-variety make-to-order production of assembled products with parallel component preparation. Three alternatives are compared using a common reference shift comprising 151 product units in the main flow. The approach integrates manufacturing execution system (MES) data, analysis of material routes and operator walking paths, component preparation, and multi-criteria assessment. The preferred alternative, C, reduces the modelled total operator walking distance from 61,446 to 42,587 m per shift, a reduction of 30.7%, and the total material route length from 388 to 280 m, a reduction of 27.8%. A five-criterion assessment confirms C as the preferred techno-economic alternative. Safety requirements are treated separately as mandatory implementation constraints. The potential time released is equivalent to 4.44 person-hours per shift, with an annual cost equivalent of approximately CZK 0.784 million under the reference workload. Economic scenarios account for the proportion of this potential converted into cash savings. The results provide a basis for selecting an alternative and planning its implementation.

Keywords: production layout; make-to-order production; material flow; component preparation; MES.

1. Introduction

High-variety make-to-order production of assembled products combines the need to meet diverse order requirements with the need for a smooth sequence of production operations. Individual configurations may differ in dimensions, features, and the extent of component preparation, thereby changing the requirements for workstations, handling space, and assembly feeding. Production system assessment must therefore consider not only equipment placement, but also the production mix, operation frequencies, and the relationships between successive processes [1], [2], [3].

The interface between preparatory workstations and main assembly requires particular attention. The decision to prepare components in kits or retrieve them from line-side stock affects not only material routes, but also operator walking

Working Paper of 37th DAAAM Symposium

distances and workloads [4], [5], [6]. In a system with parallel branches, the supply of the correct components must also be synchronised with the progress of each product unit [1]. In this study, rationalisation is therefore understood as the joint modification of the layout, component preparation, and information transfer rules, rather than merely a reduction in inter-workstation distances.

The case study concerns a production system in which changes in order volume and mix were not adequately reflected in the workstation layout and assembly feeding arrangements. This resulted in backtracking and intersecting flows, walking around workbenches, and handling movements required solely for product identification [1]. The objective is to compare three integrated layout and organisational alternatives while retaining the existing technologies and respecting the constraints of the production hall.

Systematic Layout Planning, as described by Muther and Hales [2], links products, quantities, operation sequences, and space requirements. This study adopts a similar logic for defining flows and comparing alternatives at a level appropriate to the production system under consideration. Pérez-Gosende, Mula, and Díaz-Madroñero [3] jointly consider handling and rearrangement costs, departmental proximity, and space utilisation. A key implication for the present case is that the shortest material route does not necessarily provide the best overall solution.

Assembly layout is closely related to the method of component preparation. Limère, Van Landeghem, and Goetschalckx [4] incorporate variable operator walking distances into the choice between kitting and line stocking. Schmid, Montreuil, and Limère [5] integrate assembly task allocation, line feeding, and space requirements. Adenipekun, Limère, and Schmid [6] apply integrated decision-making on part feeding and internal transportation in an industrial enterprise. These findings highlight the need to account for the work generated in pre-assembly: eliminating walking at main assembly is not beneficial if it merely transfers a greater labour requirement to the preceding operation.

Kotrady, Gabštur, Kočiško, Pollák, and Kaščak [7] use discrete-event simulation of an assembly line to identify bottlenecks and balance operator and equipment utilisation. For the production system examined here, this approach provides a suitable extension of the analysis when validating the coordination of preparatory and assembly operations.

Grznár et al. [8] link the sizing of inter-operation buffers to the assessment of work-in-progress, downtime, and costs. For the present case, this highlights the need to validate rack capacity and the release rules for component preparation, rather than considering only geometric route lengths.

Lind et al. [9], [10] extend layout optimisation to include human factors and the assessment of working conditions. Physical workload and ergonomic operating conditions should therefore be assessed alongside walking distance.

Müller et al. [11] integrate technical and economic perspectives in the design of a robotic plasma cutting workstation by combining baseline analysis, layout design, multi-criteria assessment, and payback evaluation. Malaga, Broum, and Ulrych [12] present a cost-oriented approach using simulation, a layout design tool, and an enterprise resource planning (ERP) system. The shared principle of evaluating layout changes together with their cost implications at the alternative-selection stage is relevant to the present study.

The contribution of this paper is an integrated approach to comparing layout alternatives in make-to-order production, combining a common shift basis, layout changes, component preparation, and information-based flow control. The techno-economic assessment is complemented by an evaluation of safety requirements and scenarios for using the released labour capacity, thereby providing a basis for implementation planning.

2. Case study, data sources and methodology

This section defines the production system under study, the data period, and the common shift basis. It then specifies the measures of operator and material movement and the assumptions used in their comparison.

2.1. Production system and scope

The enterprise is hereafter referred to as Company P. The product is described generically as an assembly comprising longitudinal structural members, a flat semi-finished functional component, and fastening or optional drive elements. The main assembly and supplementary profile components follow parallel branches. The classification by dimensional and process complexity is retained, while commercial names and the specific product application are omitted. Operations P7, P8, and P9 denote tube cutting, pre-assembly, and main assembly, respectively [1].

The assessment covers the operations examined in both production branches and the links between them [1]. Connections to adjacent processing areas are included in the defined routes; the total operating costs of those areas are outside the scope of the calculation.

2.2. Data period and reference shift basis

The reference period for the analysis is January–October 2024; annual summaries and other time windows are considered separately. Production times are aggregated from the MES, and operator walking paths were determined from observations of work procedures and a 2D model in BricsCAD. Material flow relationships were assessed using Sankey diagrams, and operator movements using spaghetti diagrams [1].

A common reference shift with a baseline volume of 151 product units in the main flow is defined for all alternatives. Each process step uses its own processing frequency according to the production mix. The number of passes through the

Working Paper of 37th DAAAM Symposium

parallel profile branch is recorded separately and is not added to the number of finished products. Table 1 summarises the production groups, their reference shift volumes, and the selected operation frequencies.

Group / operation	Characteristics	Units / shift
G1	Standard configurations; dimensional threshold of 2.5 m	73
G2	Configurations with greater dimensional or functional complexity	62
G3	Non-standard configurations	16
Main flow total	Sum of G1–G3; baseline model volume	151
Selected operation frequencies	P7: 143; P8: 142; P9: 150; inspection: 151	Operation-specific
Parallel profile branch	Cutting: 160 passes, not 160 additional finished products	Separate frequency

Table 1. Reference shift basis [1]; production group names are generalised. Individual frequencies are rounded; the comparison uses aggregate walking distances on the same shift basis [1].

2.3. Performance measures and comparison assumptions

The index j identifies the configuration, with j = 0 denoting the baseline and j = A, B, or C denoting the proposed alternatives. Total walking distance D(j) is the sum of the distances walked by all operators included in the assessment during the reference shift, expressed in metres per shift. For operation k at station s, q(k,s) denotes the number of executions per reference shift, and d(j,k,s) is the corresponding operator walking distance per execution, in metres, under configuration j. The summation in (1) covers all operations and stations examined. The corresponding total walking time t(j) is expressed in person-hours per shift, rather than as the shift duration of a single operator, and is calculated using a reference walking speed of v = 1.18 m/s [1].

$$D(j) = \sum q(k,s) \cdot d(j,k,s); \quad t(j) = D(j) / (3{,}600 \cdot v) \tag{1}$$

The factor 3,600 converts seconds to hours. The measure L(j) is the total geometric length of the material routes examined in both branches under configuration j, expressed in metres; it is not weighted by transport frequency. For the calculation of relative reductions, X denotes either D or L, with X(0) and X(j) representing the baseline and alternative-specific values of the selected measure, respectively. The relative reduction from the baseline to alternative j, expressed as a percentage, is obtained by dividing the difference X(0) - X(j) by X(0) and multiplying the result by 100. The deterministic design model compares the alternatives using the same production mix, operation frequencies, and operating rules; the proposed routes and work organisation differ.

3. Layout and process rationalisation alternatives

All alternatives retain the product range and core production equipment. Common constraints include the fixed position of the flat-component cutting station and its associated manipulator, connections to adjacent processing areas, equipment accessibility, and space for handling large components. The layout changes in alternatives A–C [1] are assessed together with the proposed information-based control specification for implementation.

3.1. Alternative A: targeted modifications

Alternative A retains the basic structure of the existing layout. Supplementary profile cutting is relocated to an adjacent processing area alongside similar operations, accessory preparation is moved closer to packing, and the sequence of joining operations is arranged to reduce backtracking. This is the least demanding alternative, with an indicative cost of CZK 30,000 and an estimated implementation time of one day.

3.2. Alternative B: extensive reconfiguration

Alternative B relocates most workstations and the local storage area. Joining operations are grouped in a triangular configuration, and assembly stages are predominantly arranged in a direct sequence; however, backtracking from packing to the output point remains. The alternative includes parallel preparation of the tubular component in response to an MES request, rather than physically bringing a trolley to the station to scan the product identifier. Indicative implementation estimates are CZK 200,000 and five days.

Working Paper of 37th DAAAM Symposium

3.3. Alternative C: coordinated flow and component preparation

Alternative C retains the local storage area in its original position and combines grouped preparatory operations with a direct sequence of assembly, inspection, and packing. The main flow forms a broadly U-shaped functional arrangement. Component preparation is transferred from main assembly P9 to pre-assembly P8, while the fitting of the lower structural profile is transferred in the opposite direction. The prepared kit thus arrives at main assembly together with the product. A rack accessible from both sides is installed between P7 and P8; transfer from P8 to P9 continues to use a trolley. Indicative implementation estimates are CZK 60,000 and two days [1]. The functional arrangement of alternative C, including the selected main flow and its connection to tube preparation, is shown in Fig. 1. The diagram presents the process relationships in an anonymised form without reproducing the actual geometry of the production hall.

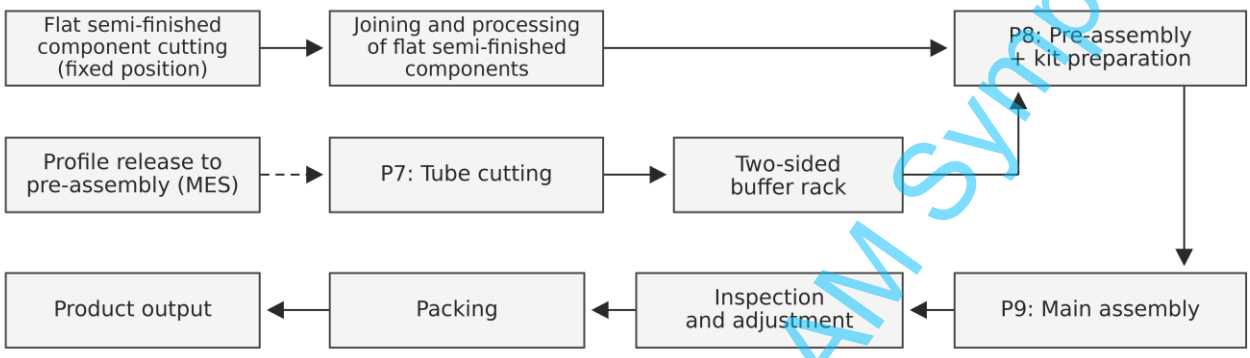

Fig. 1. Functional diagram of alternative C, prepared by the authors from the process relationships [1]. Not to scale; solid lines denote material flow and the dashed line an information request. The diagram shows the selected main flow and its connection to tube preparation.

3.4. Unified MES logic and task transfer

A common trigger is defined for alternatives B and C: the release of a set of structural profiles from the final preparatory operation to pre-assembly. For surface-treated components, this occurs after treatment is completed and quality clearance is obtained; for other components, it follows completion of mechanical preparation. The MES releases a request to P7 only when the associated components are available and the intermediate buffer has free capacity. This logic constitutes a design specification for implementation.

The request, prepared component, rack location, and trolley must be linked to a unique product-unit identifier. A repeated signal must not trigger duplicate preparation. P8 verifies that the components match and records their withdrawal; priority follows the released order sequence. Trolley movements made solely for identification are eliminated, while component identity checks are retained. The calculation assumes that the total direct labour content of the exchanged tasks remains unchanged; no separate time saving is attributed to those tasks. Rack capacity must be validated during the pilot in relation to work-in-progress and waiting at downstream workstations, rather than solely on the basis of available space [8].

4. Quantitative results and alternative selection

The alternatives are first compared in terms of movement measures and implementation requirements. The subsequent multi-criteria assessment determines their techno-economic preference, while mandatory implementation constraints are assessed separately.

4.1. Comparison of shift-based and geometric measures

Table 2 compares the alternatives on a common shift basis. Alternative C has the lowest total walking distance, material route length, and mean distance between the selected workstations and the supervisor's station. The last measure characterises workstation accessibility as one of the conditions supporting day-to-day production control.

The difference between the baseline and alternative C is 18,859 m of total walking distance per shift, 108 m of material route length, and 4.44 person-hours of walking per shift. The 30.7% reduction in walking distance represents the change in total operator movement, whereas the 27.8% reduction in material route length characterises the change in the geometry of the flows examined.

Working Paper of 37th DAAAM Symposium

Measure	Baseline	A	B	C
Total walking distance [m/shift]	61,446	52,217	47,153	42,587
Walking distance reduction [%]	—	15.02	23.26	30.69
Walking time [person-hours/shift]	14.465	12.292	11.100	10.025
Material route length [m]	388	336	318	280
Route length reduction [%]	—	13.40	18.04	27.84
Mean distance from supervisor [m]	15.9	12.5	21.9	11.7
Approx. implementation cost [CZK]	—	30,000	200,000	60,000
Approx. implementation time [days]	—	1	5	2

Table 2. Comparison of alternatives. Distances and approximate implementation estimates [1]; times and percentage changes recalculated by the authors using v = 1.18 m/s.

4.2. Separating feasibility from techno-economic preference

Mandatory safety and operational suitability requirements are treated as non-negotiable implementation constraints, separately from the scoring process. The proportion of matching responses in the validation checklist and the indicator of potential future costs (K6 and K7) [1] are therefore excluded from the final score. Safety is assessed using the procedure in Section 5, while additional costs are addressed in the budget and economic scenarios. The resulting ranking establishes techno-economic preference before final implementation approval.

The five assessment criteria retain the preference order K1, K5, K2, K3, and K4, from highest to lowest importance, and the ratios of their unnormalised weights [1]. After renormalisation, the weights for K1, K2, K3, K4, and K5 are 7/25, 5/25, 4/25, 3/25, and 6/25, respectively. Weighted rank scoring is applied. Since all criteria are minimised, the best-performing alternative receives three points, the middle alternative two, and the lowest-ranked alternative one. Ties receive the mean of the points associated with the occupied ranks.

$$S(j) = \sum w(i) \cdot g(i,j); \quad \sum w(i) = 1 \tag{2}$$

In (2), S(j) is the dimensionless overall weighted score of alternative j, where j denotes A, B, or C. The index i runs from 1 to 5 and corresponds to criteria K1 to K5 in this order. The term w(i) denotes the normalised weight of criterion i, and g(i,j) denotes the rank-based point score assigned to alternative j for criterion i. Both summations cover all five criteria, and the weights sum to one. A higher value of S(j) indicates a stronger techno-economic preference. Table 3 presents the criterion weights, assigned points, and overall weighted scores.

Criterion	Weight	Points A	Points B	Points C
K1 – total walking distance	7/25	1	2	3
K2 – approx. implementation cost	5/25	3	1	2
K3 – approx. implementation time	4/25	3	1	2
K4 – distance from supervisor	3/25	2	1	3
K5 – material route length	6/25	1	2	3
Overall weighted score	**1**	**1.840**	**1.520**	**2.640**

Table 3. Scoring of the five criteria; all criteria are minimised. A higher overall score indicates a stronger preference.

The resulting ranking is C–A–B. With equal weights for all five criteria, the scores are A = 2.000, B = 1.400, and C = 2.600. When the cost and implementation-time weights are both multiplied by a factor α and then renormalised, A and C tie at $\alpha = 29/9 \approx 3.22$; greater emphasis on these two measures favours A. The preference for alternative C therefore applies to the specified priorities and the alternatives compared.

5. Safety, ergonomics and implementation requirements

Alternative selection is conditional on documented safety and operational suitability. The following procedure links approval checkpoints to implementation preparation and organisation.

Working Paper of 37th DAAAM Symposium

5.1. Validation checklist as an approval requirement

The validation checklist separates mandatory requirements from preferences concerning the extent of changes, such as relocating a noise source. The proposed eighteen checkpoints focus on documenting compliance with individual requirements and closing the associated actions. The approach is based on prevention, risk assessment, and adapting work to the individual, as defined in the occupational safety and health (OSH) framework [13].

Each item includes the requirement, the evidence used in its assessment, the responsible person, its status, a corrective action, and a closure record. The statuses are "compliant", "further evidence required", "non-compliant", and "not applicable, with justification". For mandatory items, both "non-compliant" and "further evidence required" prevent the affected part of the change from being released into operation. The decision is not based on an average compliance percentage. Table 4 summarises the 18 proposed checkpoints by assessment area, together with the requirements to be documented and the responsible specialist roles.

Area / items	Requirements to be documented	Responsible specialist role
Fire safety 1–3	1. Escape routes. 2. Access to fire safety equipment. 3. Compliance with the building's fire safety design and designated use.	Qualified fire safety specialist and facilities management
Handling and storage 4–6	4. Travel paths and handling areas for the largest components. 5. Conflicts between pedestrian and trolley movements. 6. Stability and capacity of racks and buffers.	Process engineer, production and OSH personnel
Ergonomics and operation 7–9	7. Load weight and frequency of manual handling. 8. Reach distances, working postures and heights. 9. Safe operation and access to emergency stops.	OSH / ergonomics specialist and manufacturing engineer
Working environment 10–13	10. Noise. 11. Vibration. 12. Dust and extraction. 13. Lighting and workspace. The scope of measurements is determined by the risk assessment.	OSH personnel and the relevant specialist
Technical infrastructure 14–15	14. Utility and data connections, including required inspections. 15. Maintenance access and safe equipment isolation.	Maintenance, facilities management and the relevant qualified inspector
Organisational readiness 16–18	16. Updated risk assessment. 17. Work standards, qualifications and training. 18. Documented action closure and release into operation.	Production management, with approval by the relevant specialists

Table 4. Proposed structure of the 18 checkpoints for implementation approval.

Specific dimensional, occupational hygiene, and technical limits are determined by the actual equipment, the components handled, the applicable requirements, and the building documentation. Relocating noisy equipment requires an exposure assessment and, where necessary, corrective measures. The outcome of the specialist assessment determines whether the change can be released into operation.

5.2. Proposed implementation arrangements

For alternative C, preparatory activities are scheduled outside the relocation window: finalising work standards for P8 and P9, labelling rack locations and trolleys, testing the MES logic, preparing the required connections, and assessing risks. The proposed implementation plan treats two days as an indicative window for physical reconfiguration. Preparation, training, and stabilisation are separate stages; this allocation of time is a planning assumption.

Following equipment relocation, technical inspection and controlled trial operation take place once the relevant safety requirements have been satisfied. Ramp-up to full capacity forms part of the stabilisation stage. For information system outages, a controlled fallback recording procedure is proposed, using the same identifiers and subsequent record reconciliation to prevent duplicate component requests. Ergonomic conditions and the risk of product damage will be evaluated separately during pilot operation.

Working Paper of 37th DAAAM Symposium

6. Economic valuation and planning budget

The economic assessment distinguishes between the value of released labour capacity, implementation costs, and actual monetary benefits. The payback scenarios account for the proportion of the calculated potential that translates into expenditure savings.

6.1. Value of potentially released capacity

The economic model uses a reference walking speed of v = 1.18 m/s and an hourly labour cost rate of c = CZK 352 per person-hour [1]. The annual scenario comprises 251 working days and two shifts per day, giving N = 502 reference shifts per year. The calculation retains the project's price level and historical working-time assumptions. In the baseline annual scenario, each shift is treated as equivalent to the reference shift defined in Section 2.

$$\Delta t = [D(0) - D(C)] / (3{,}600 \cdot v); \quad U = \Delta t \cdot c \cdot N \tag{3}$$

In (3), D(0) and D(C) denote the total operator walking distances in the baseline and alternative C, respectively, expressed in metres per reference shift. The quantity Δt denotes the walking time potentially released by alternative C, in person-hours per shift, and U is the annual labour-cost equivalent of this potentially released capacity, in CZK per year. The factor 3,600 converts seconds to hours.

Using unrounded intermediate values, the calculation gives Δt = 4.4395 person-hours per shift, equivalent to approximately 2,228.6 person-hours per year. The annual cost equivalent of walking is CZK 2,555,968 in the baseline and CZK 1,771,491 for alternative C. The difference, calculated before rounding, is U = CZK 784,478 per year. This amount represents the value of potentially released labour capacity; its conversion into a monetary benefit is examined in Section 6.3.

6.2. Extended implementation cost estimate

For the economic assessment of alternative C, an extended planning budget of CZK 100,000 is considered alongside the indicative implementation cost of CZK 60,000 [1]. It includes additional allowances for MES modifications, testing, training, and compliance checks. The additional amounts in Table 5 constitute an author-defined budget scenario at the project's price level for implementation planning.

Budget item	Amount [CZK]	Status
Base allowance for relocation and workstation modifications	60,000	Original approximate estimate
Additional allowance for MES modifications, testing and training	20,000	New planning assumption
Contingency for inspections, measurements and minor corrective actions	20,000	New planning assumption
Total planning budget	**100,000**	**Economic assessment scenario**

Table 5. Planning budget for alternative C: indicative relocation costs [1] and additional budget assumptions.

Each item must be counted only once in the subsequent budget. Any overlap with the original estimate must be removed; major building alterations, extensive software development, lost production, or costly safety measures require a revised estimate. A conveyor between P8 and P9 is included in neither the design nor the budget. The scoring comparison in Section 4 uses the original approximate estimates for all alternatives; increasing the budget for C to CZK 100,000 does not, by itself, change its cost ranking between A and B.

6.3. Converting capacity into monetary benefits

The coefficient β represents workload relative to the reference annual scenario at the same production mix, while η is the proportion of the capacity equivalent actually converted into cash savings. Both coefficients are dimensionless. The quantity Δt_a denotes the additional labour requirement outside the walking model, in person-hours per shift, and C_a denotes additional annual operating costs, in CZK per year. The implementation investment is denoted by I, in CZK. The quantities Δt, c, and N retain the definitions and reference values used in Section 6.1. The net annual cash benefit G, in CZK per year, and the simple payback period P, in months, are calculated using (4). The payback period is defined only when G is positive.

$$G = \eta \cdot (\beta \cdot \Delta t - \Delta t_a) \cdot c \cdot N - C_a; \quad P = 12 \cdot I / G, for\ G > 0 \tag{4}$$

Working Paper of 37th DAAAM Symposium

The factor 12 converts the payback period from years to months. Table 6 presents illustrative scenarios for different investment amounts, workloads, and proportions of the capacity equivalent converted into cash savings. The additional labour requirement Δt_a and additional annual operating costs C_a are both set to zero in all scenarios shown.

Investment I [CZK]	Workload β	Realisation η	G [CZK/year]	P [months]
60,000	100%	100%	784,478	0.92
100,000	100%	100%	784,478	1.53
100,000	100%	50%	392,239	3.06
100,000	100%	25%	196,119	6.12
100,000	80%	25%	156,896	7.65

Table 6. Illustrative economic scenarios; $\Delta t_a = 0$ and $C_a = 0$ in all rows.

Cash savings may arise, for example, from reducing paid overtime or external labour support. Without such a change, $\eta = 0$, and no savings-based payback occurs. Higher output is a separate capacity benefit, not automatically an expenditure saving. For I = CZK 100,000 and zero additional costs, payback within one year requires at least 12.75% of the reference equivalent to be realised as cash savings.

7. Discussion and proposed operational validation

The discussion examines the contribution of the integrated measures and the sensitivity of the results to the model assumptions. The proposed pilot protocol links the design assessment to validation of the results and operational stabilisation.

7.1. Integrating layout, assembly feeding and work organisation

Alternative C combines layout changes with component preparation and information-based production release. Its advantage extends beyond arranging workbenches in a U-shape. Pre-assembly takes over kit preparation, main assembly incorporates profile fitting, and P7 receives a request without unnecessary trolley movement. This principle is consistent with the joint assessment of assembly tasks and line feeding [4], [5], [6]. Retaining the local storage area also limits the extent of the intervention compared with B.

The alternatives are evaluated as integrated sets of layout and organisational measures; the calculated benefits therefore represent their combined effect. The aspects most transferable to other applications are the use of consistent operation volumes, assessment of both successive workstations, and the distinction between capacity potential and its monetary realisation. The magnitude of the savings depends on the specific production mix and operating arrangements.

7.2. Assessment assumptions and result sensitivity

The assessment is a deterministic design study based on aggregated shift data. Aggregated MES times characterise the production system, while the benefit calculation uses operation frequencies and operator walking paths. Operational variability and the stability of the results are addressed through the subsequent pilot validation.

An identical production mix provides a common basis for comparing the alternatives. When all frequencies are scaled uniformly and the routes remain unchanged, relative savings in the linear model remain constant, while the absolute benefit increases or decreases with workload. Changes in the proportions of dimensional groups, batching, queues, or feeding arrangements require a corresponding model update.

Balancing capacity between P8 and P9 is an important condition for realising the benefit of task transfers. An additional half person-hour of work per shift, beyond the walking time already included, would reduce the annual capacity equivalent by CZK 88,352 under the reference parameters, before applying η. The time saved is distributed across several operators, and its utilisation therefore requires corresponding adjustments to work organisation.

7.3. Proposed pilot protocol

The pilot should compare the baseline and modified configurations with comparable proportions of groups G1–G3, similar staffing, and identical operation definitions. Walking, handling, direct assembly, waiting, and rework should be recorded separately. The sample size should be determined from the variability of the initial measurements. MES records should be checked for complete identifiers and timestamps, duplicates, and entries without completion records; repairs and downtime should be recorded separately. Based on time distributions, the pilot can be supplemented with discrete-event simulation to assess bottlenecks and workstation utilisation [7].

Working Paper of 37th DAAAM Symposium

To monitor stochastic arrival fluctuations, the pilot should extend MES logging, supplemented by time-stamped operator observations, to link each product-unit identifier to the P7 request, tube completion, rack deposit and withdrawal, arrivals of the other required components at P8, and P8 start and completion. A common clock should be used. Inter-arrival times for each incoming stream and request-to-rack lead times should be summarised by shift and groups G1–G3 using the mean, coefficient of variation (standard deviation divided by the mean), and 95th percentile. Batch arrivals should remain identifiable rather than being averaged into a uniform arrival rate.

Rack occupancy should be reconstructed from the initial stock and every deposit and withdrawal, distinguishing total stock from components matching the released sequence. At each staffed P8 workstation, starvation should be logged from the instant the workstation is ready for the next released unit but a required matching component is unavailable until this condition ends; an empty rack alone is not sufficient evidence. Operator reason codes should distinguish missing tubes from other missing inputs, equipment downtime, and downstream blocking. Each shift should report starvation-event count, total and maximum duration, and total starvation time divided by scheduled, staffed production time excluding planned breaks, alongside time-weighted rack occupancy and empty/full-buffer durations. Production and process engineering should review these measures after each pilot shift and use persistent shortages to revise release timing, rack capacity, or task allocation, checking P9 throughput and work-in-progress. These are proposed validation measures, not observed stochastic results; the reported walking-time saving remains a deterministic estimate.

Validation must cover the combined labour content of P7–P9, the workload at P8, correct component matching, repeated signals, rack occupancy, and cancelled units or units undergoing repair. Work-in-progress, throughput, internal non-conformities, and the use of released hours should also be monitored. Calculation verification is complemented by validation of the model's agreement with actual operations [14]. The economic assessment values only the released walking time; separate valuation of material routes could double-count the same handling activity. Scrap rate, production floor area, and lead time are additional measures to be monitored separately and are not included in the reported economic result.

A related system-level perspective is presented by Kremljak [15], who examines the integration of machining and assembly systems through changes to equipment placement, logistics routes, and coordination. In the present case, the pilot should assess the links between component preparation and main assembly, rather than evaluating each workstation in isolation.

Attia et al. [16] use discrete-event simulation to compare one-piece flow, unnecessary motion reduction, their combination, and cellular manufacturing. In their production line, where automatic and semi-automatic machines dominate, reducing human motions alone yields only a small productivity improvement. This reinforces the need to evaluate walking-time reductions separately from changes in throughput, workstation utilisation, and work-in-progress during the proposed pilot.

8. Conclusion

For the reference shift comprising 151 units in the main flow, alternative C emerges as the preferred solution among the three alternatives compared. The model projects a 30.7% reduction in total walking distance, a 27.8% reduction in material route length, and the release of 4.44 person-hours per shift. The five-criterion assessment produces the ranking C–A–B; giving greater priority to low cost and short implementation time may favour A. The key feature is the integration of layout, component preparation, and flow control based on unique product identification.

The annual cost equivalent of approximately CZK 0.784 million expresses the value of the capacity potential under the reference workload. With the proposed planning budget of CZK 100,000 and conversion of 25–50% of this potential into cash savings, the modelled simple payback period ranges from 3.06 to 6.12 months, excluding additional operating costs. Alternative C is recommended for controlled implementation planning and pilot operation once compliance with the mandatory safety requirements has been documented.

9. Acknowledgments

This publication was created with financial support from the University of West Bohemia in Pilsen for the long-term conceptual development of the research organisation.

10. References

[1] Hlaváček, Š. (2025). Návrh racionalizace layoutu výrobní linky v průmyslovém podniku [Proposal for the rationalisation of a production line layout in an industrial enterprise], Master's thesis (in Czech), Faculty of Mechanical Engineering, University of West Bohemia, Pilsen, Czech Republic.

[2] Muther, R. & Hales, L. (2015). Systematic Layout Planning, 4th edition, Management & Industrial Research Publications, ISBN 978-0-933684-06-5, Marietta, Georgia, USA.

[3] Perez-Gosende, P.; Mula, J. & Díaz-Madroñero, M. (2024). A bottom-up multi-objective optimisation approach to dynamic facility layout planning. International Journal of Production Research, Vol. 62, No. 3, pp. 626-643, ISSN 0020-7543, DOI: 10.1080/00207543.2023.2168308.

Working Paper of 37th DAAAM Symposium

[4] Limère, V.; Van Landeghem, H. & Goetschalckx, M. (2015). A decision model for kitting and line stocking with variable operator walking distances. Assembly Automation, Vol. 35, No. 1, pp. 47-56, ISSN 0144-5154, DOI: 10.1108/AA-05-2014-043.
[5] Schmid, N. A.; Montreuil, B. & Limère, V. (2024). Modeling and solving integrated assembly line balancing, assembly line feeding, and facility sizing problems. International Journal of Production Economics, Vol. 277, Article No. 109354, ISSN 0925-5273, DOI: 10.1016/j.ijpe.2024.109354.
[6] Adenipekun, E. O.; Limère, V. & Schmid, N. A. (2025). Part feeding and internal transportation decision making for a machinery manufacturer. INFORMS Journal on Applied Analytics, Vol. 55, No. 2, pp. 154-177, ISSN 2644-0865, DOI: 10.1287/inte.2023.0039.
[7] Kotrady, V.; Gabštur, P.; Kočiško, M.; Pollák, M. & Kaščak, J. (2026). Simulation-based optimization of assembly line efficiency through intelligent operator rotation and resource utilization balancing. Journal of Manufacturing and Materials Processing, Vol. 10, No. 4, Article No. 132, ISSN 2504-4494, DOI: 10.3390/jmmp10040132.
[8] Grznár, P.; Gregor, M.; Mozol, Š.; Krajčovič, M.; Dulina, Ľ.; Gašo, M. & Major, M. (2019). A system to determine the optimal work-in-progress inventory stored in interoperation manufacturing buffers. Sustainability, Vol. 11, No. 14, Article No. 3949, ISSN 2071-1050, DOI: 10.3390/su11143949.
[9] Lind, A.; Elango, V.; Hanson, L.; Högberg, D.; Lämkull, D.; Mårtensson, P. & Syberfeldt, A. (2024). Multi-objective optimization of an assembly layout using nature-inspired algorithms and a digital human modeling tool. IISE Transactions on Occupational Ergonomics and Human Factors, Vol. 12, No. 3, pp. 175-188, ISSN 2472-5838, DOI: 10.1080/24725838.2024.2362726.
[10] Lind, A.; Elango, V.; Bandaru, S.; Hanson, L. & Högberg, D. (2024). Enhanced decision support for multi-objective factory layout optimization: integrating human well-being and system performance analysis. Applied Sciences, Vol. 14, No. 22, Article No. 10736, ISSN 2076-3417, DOI: 10.3390/app142210736.
[11] Müller, J.; Broum, T.; Malaga, M. & Milatová, M. (2025). Integrating robotic systems into a plasma cutting workstation - new workstation design approach using techno-economic evaluation. Tehnički glasnik, Vol. 19, No. 3, pp. 481-488, ISSN 1846-6168, DOI: 10.31803/tg-20240517165802.
[12] Malaga, M.; Broum, T. & Ulrych, Z. (2022). Cost-related industrial project design using simulation, layout design and an ERP system, Proceedings of the 2022 International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA), 9-11 June 2022, Ankara, Turkey, ISBN 978-1-6654-6835-0, pp. 1-4, IEEE, Piscataway, New Jersey, USA, DOI: 10.1109/HORA55278.2022.9799830.
[13] European Agency for Safety and Health at Work (EU-OSHA) (2021). Directive 89/391/EEC - OSH "Framework Directive", Available from: https://osha.europa.eu/en/legislation/directives/the-osh-framework-directive/1, Accessed: 2026-09-22.
[14] Sargent, R. G. (2013). Verification and validation of simulation models. Journal of Simulation, Vol. 7, No. 1, pp. 12-24, ISSN 1747-7778, DOI: 10.1057/jos.2012.20.
[15] Kremljak, Z. (2025). Production process layout optimization when combining two existent systems, In: DAAAM International Scientific Book 2025, Katalinic, B. (Ed.), Chapter 03, pp. 035-046, DAAAM International, ISBN 978-3-902734-45-7, ISSN 1726-9687, Vienna, Austria, DOI: 10.2507/daaam.scibook.2025.03.
[16] Attia, E.-A.; Sobhi, N.; Alarjani, A. & Karam, A. (2023). Improving electric motor assembly using one piece flow, ergonomics, and cellular layout. International Journal of Simulation Modelling, Vol. 22, No. 2, pp. 255-266, ISSN 1726-4529, DOI: 10.2507/IJSIMM22-2-643.

Working Paper of 37th DAAAM Symposium