A Constructive Heuristic with Local Search and Quality Function Deployment for the User-Centred Design of Assembly Lines Employing Workers with Cognitive Disabilities

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ABSTRACT

Six out of ten working-age people with disabilities remain outside the labour market in Mexico. Those who do join a production line encounter work plans computed without regard for the fact that people differ from one another, because assembly line balancing models with heterogeneous workers represent each operator by a single value: their mean time. Two workers with the same mean are not equivalent in daily operation if one delivers within a narrow band and the other varies considerably between repetitions. This study incorporates individual performance dispersion as a criterion within the assignment decision and proposes a multi-start constructive heuristic with local search, developed under a user-centred design approach and integrated with quality function deployment. Design requirements were derived from normative and literature sources, and their prioritisation placed time reservation as the highest-priority technical requirement. The method decides using an effective time equal to the mean plus k standard deviations, so that a single parameter reserves a wide margin for an irregular worker and a minimal one for a consistent worker, while a value of zero reproduces the classical method exactly. Monte Carlo evaluation over 124 instances from the four benchmark families shows that the proportion of cycles meeting the committed time rises from 9.9 to 79.4 per cent, and that performance variation falls by between 29 and 45 per cent. A control test with a homogeneous workforce yields a difference of 0.00 per cent, confirming that the advantage stems from differences between people and not from having added slack to the plan.

Keywords: assembly line balancing, cognitive disability, user-centred design, quality function deployment, constructive heuristic.

INTRODUCTION

Approximately 1.3 billion people, one in six worldwide, live with a significant disability (World Health Organization [WHO], 2023). The figure does not describe a marginal minority but the largest group facing systematic barriers to exercising a right explicitly recognised in Article 27 of the Convention on the Rights of Persons with Disabilities (United Nations [UN], 2006): to work on an equal basis with others, in a labour market and work environment that are open and accessible.

In Mexico, the distance between that right and its exercise can be measured precisely. The 2020 Population and Housing Census recorded 7,168,178 people with a disability or mental condition, 5.7 per cent of the national population. Among them, the labour force participation rate was 38 per cent, against 67 per cent among people without disabilities (Instituto Nacional de Estadística y Geografía [INEGI], 2021). Put differently, of every ten working-age people with disabilities barely four participate in the labour market, whereas among the rest almost seven do.

Much institutional effort has concentrated on narrowing that gap at its point of entry, that is, on getting firms to hire. This is a legitimate priority, yet it leaves unanswered a second question that is rarely posed: what happens to those who do get in. Whoever does arrives at a production line designed for an average body and an average

pace, under a work plan computed without considering that people differ from one another.

The current normative framework illustrates clearly where present coverage ends. NOM-034-STPS-2016 establishes safety conditions for the access and performance of activities by workers with disabilities in Mexican workplaces (Secretaría del Trabajo y Previsión Social [STPS], 2016), while ISO 21542 regulates the accessibility of the built environment (International Organization for Standardization [ISO], 2021) and ISO 21801-1 guides the design of cognitively accessible systems (ISO, 2020). All three are indispensable and all three share a limit: they govern the building, the signage and the comprehension of the task, but none determines how the workload is to be distributed among stations. Access is regulated; assignment is not.

Industrial engineering has addressed that second problem, although incompletely. The assembly line worker assignment and balancing problem, known as ALWABP, was formulated precisely for sheltered work centres employing people with disabilities and allows the time of each operation to depend on who performs it (Miralles et al., 2008). Later developments refined solution methods through heuristics and metaheuristics (Moreira et al., 2012) and incorporated robust formulations against uncertainty (Moreira et al., 2015).

However, all those models share one simplification: they represent each worker by a single number, their mean time. Two people may take the same time on average and yet not be equivalent in daily operation, because one delivers consistently within a narrow band while the other varies considerably from one repetition to the next. To the model they are identical, so the planner treats them alike and assigns them the same load. When the station is overrun, and it is overrun frequently because variability accumulates along the line, the model does not record that the error was its own.

To this is added a consequence that is seldom accounted for. The failure to comply falls not on the plan that produced it but on the person, who is singled out as someone who does not perform, does not adapt or holds the group back. Moreover, a firm that attributes that outcome to inclusion itself is unlikely to attempt it again, so that a design error ends up producing false evidence against hiring.

Designing otherwise therefore requires placing whoever will occupy the post at the centre of the decisions. User-centred design, whose principles and process are established in ISO 9241-210 (ISO, 2019), holds that the characteristics and needs of the people who will use a system must guide its development. Among the techniques that operationalise it, quality function deployment translates user-expressed needs into verifiable technical requirements (Akao, 1990; Hauser and Clausing, 1988); its use taking people with disabilities as the voice of the customer, by contrast, remains scarce.

This article therefore proposes a constructive heuristic with local search for the design of inclusive workstations, developed under a user-centred approach and integrated with quality function deployment. The general objective is to determine whether incorporating individual performance dispersion into the assignment criterion improves the reliability of the line. The specific objectives are to delimit the research gap through a systematic review, to derive and prioritise the design requirements, to characterise the range of individual dispersion, and to evaluate the proposed method experimentally against the classical one.

LITERATURE REVIEW

The Worker Assignment and Balancing Problem with Heterogeneous Workers

Assembly line balancing consists of distributing a set of operations among workstations, respecting the order in which they must be performed, so that no station becomes a bottleneck. The measure to be controlled is the cycle time, determined by the most heavily loaded station. The classical formulation rests on an assumption that is seldom discussed: that each operation takes the same time regardless of who performs it.

Miralles et al. (2008) broke that assumption by formulating the ALWABP, in which the time of each operation depends on the worker performing it and in which certain task-worker combinations are infeasible. The motivation was explicitly social: sheltered work centres employing people with disabilities. Araújo et al. (2015) extended the formulation to parallel lines while retaining that same study population.

Because the problem is computationally hard, subsequent literature concentrated on approximate methods. Moreira et al. (2012) proposed simple constructive heuristics with priority rules, and Demirkol Akyol and Baykasoğlu (2019) developed a multiple-rule constructive randomised procedure that constitutes the closest methodological reference to the approach adopted here. Michels and Costa (2024) carried the formulation to multi-manned stations under the notion of worker integration.

The Treatment of Uncertainty

A second strand of work has incorporated uncertainty into the problem, although along routes that should be distinguished. The first is robust optimisation. Moreira et al. (2015) represented times through intervals with a robustness budget, and Yılmaz (2020) combined interval and polyhedral sets for a U-shaped line. In both cases the protection against the worst case is determined by a parameter the planner sets, not by a characterisation of each person's behaviour.

The second route is stochastic programming, and it is notable that it has located randomness not in the duration of the task but in the presence of the worker. Ritt et al. (2016) modelled stochastic worker availability through a two-stage scenario-based programme, and Liu et al. (2022) extended that formulation with risk aversion and temporary workers, in a context of absenteeism among workers with disabilities. In both, the random variable is whether the worker attends, not how much their performance varies when they do.

More recently, Şahin (2026) and Şahin and Söylemez (2026) have deliberately manipulated what the literature calls task time variability, classifying instances into low, medium and high levels. The scope of that notion deserves precision, because the delimitation of the present work depends on it: what the benchmark protocol calls variability is the dispersion of mean times across different workers, that is, how far apart they stand from one another in average performance. It does not refer to the dispersion of each person with respect to themselves over successive repetitions, which is a distinct quantity and one that no reviewed study incorporates into the model.

Individual Characterisation of the Worker

In parallel, another strand has enriched the description of the operator beyond their mean time. Campana et al. (2022) incorporated hierarchical qualification levels that determine both time and cost. Katiraee et al. (2023) modelled expertise and personal limits of perceived physical effort, and introduced the figure of the worker who supports novices. Cais et al. (2025) went further by distinguishing disability profiles with compatibility matrices and differentiated personal rest allowances, and Türkkan and Yılmaz (2026) added an objective of equity in workload distribution, motivated by sheltered work centres.

The pattern emerging from both strands delimits the unoccupied space precisely. Uncertainty has been modelled, but over the system or over attendance; heterogeneity has been modelled, but as a difference between the means of different people; and individual attributes have been enriched, but treated deterministically. No study characterises the dispersion of each person with respect to their own mean, nor employs it as a criterion for deciding what margin to reserve for them.

THEORETICAL FRAMEWORK

The framework guiding this study combines two conceptual bodies. The first is user-centred design, whose process and principles are established in ISO 9241-210 (ISO, 2019): design must be based on an explicit understanding of users and their tasks, involve them throughout development, and be refined through evaluative iterations. Applied to the workstation, that approach shifts the question from how to make the person fit the line to how to design the line from what the person needs.

The second is quality function deployment, a technique developed by Akao (1990) and disseminated by Hauser and Clausing (1988), which translates user needs, expressed in their own language, into measurable technical requirements. The house of quality matrix weights each need, evaluates the intensity with which each

requirement addresses it, and derives from this a hierarchy of priorities. Its value for this work lies in the fact that the resulting hierarchy does not come from the researcher's judgement but from the stated needs.

Both bodies articulate with cognitive accessibility. ISO 21801-1 (ISO, 2020) establishes guidelines for designing systems that are understandable and usable by people with cognitive disabilities, and devotes its Clause 7 to action, where it explicitly includes support for planning, time management and task completion. That clause provides the conceptual bridge between the standard and the technical object of this study, since the time margin a station reserves for an operator is, in the standard's terms, a form of support for completing the task.

METHODOLOGY

Type and Approach of the Research

In terms of its purpose, this research is applied, since it does not seek to extend theoretical knowledge of the balancing problem but to resolve a concrete deficiency in the design of workstations in environments with a heterogeneous workforce. In terms of its scope, and following the classification of Hernández-Sampieri and Mendoza Torres (2018), the study combines a descriptive moment, intended to characterise design needs and performance variability, with an explanatory one, aimed at establishing whether incorporating that variability into the assignment criterion modifies the behaviour of the line.

As to its approach, the study is mixed and adopts an exploratory sequential design in the terms described by Creswell and Creswell (2018). The qualitative phase precedes the quantitative one because design requirements cannot be assumed: they must be derived from analysis of the needs of those who will occupy the post.

Its findings then feed a computational experiment that contrasts both assignment methods under controlled conditions. Regarding experimental design, the qualitative phase is non-experimental and documentary in nature, since needs are obtained from the analysis of normative and literature sources without manipulating any variable. The quantitative phase is experimental by simulation: the margin parameter is deliberately manipulated while all other conditions remain constant, which allows the observed differences to be attributed to that manipulation and not to external factors.

Study Variables

The research works with two independent variables, three dependent, one intervening and two control variables. Table 1 presents their operational definition, measurement scale and the instrument through which each is obtained.

Table 1: Operationalisation of the study variables

Variable	Type	Operational definition	Scale	Instrument
Individual coefficient of variation (cv)	Independent, attribute	Ratio of the standard deviation to the mean of the time a worker takes on an operation	Ratio	Values documented in the literature
Margin parameter (k)	Independent, manipulated	Number of standard deviations the algorithm reserves when computing each worker's effective time	Ratio	Algorithm configuration
Technical priority of the requirement	Intervening	Sum of the products of each need's weight and the intensity of its relationship with the requirement	Ratio	House of quality (QFD)
Compliance with the committed time	Dependent	Proportion of simulated cycles whose time does not exceed the cycle time the method promises	Ratio (%)	Monte Carlo simulation
Cycle time at the 95th percentile	Dependent	Value below which 95 per cent of the simulated cycles fall	Ratio (s)	Monte Carlo simulation

Dispersion of line performance	Dependent	Standard deviation of the cycle time across simulation runs	Ratio (s)	Monte Carlo simulation
Line size	Control	Number of operations making up the instance	Ratio	Generation protocol
Order strength	Control	Density of the precedence relations in the instance graph	Ratio	Generation protocol

Source: own elaboration.

The relationship between the two independent variables deserves emphasis, since the contribution of this work

rests on it. The coefficient of variation is an attribute of each person and is not manipulated. The margin parameter is manipulated, and when multiplied by each worker's own deviation it produces a different margin for each of them. In this way, a value of zero reproduces the classical method exactly, and any observed difference can only come from individual dispersion.

Literature Search and Selection Strategy

The identification of related work was carried out in accordance with the PRISMA protocol (Page et al., 2021). This choice responds to the fact that it establishes a verifiable reporting procedure, with explicit eligibility criteria and a flow diagram documenting how many records were identified, how many were discarded and for what reason. For a review that underpins the existence of a knowledge gap, such traceability is indispensable.

The search was executed over open-access sources, so that any reader may reproduce it without requiring an institutional subscription. SciELO and Redalyc were consulted as the Ibero-American regional component, and DOAJ, DergiPark, arXiv, RePEc, MDPI, AIMS Press, RAIRO-Operations Research and journals on OJS platforms as the international component. The search string combined terms of the problem and of the population, restricted to peer-reviewed articles published between 2015 and 2026. Terms relating to uncertainty were deliberately excluded, since their presence or absence constitutes a classification criterion and not a search criterion: incorporating them would have restricted the set to studies already considering it and made any claim about the rest of the field untenable.

Eligibility criteria required that the work address the assignment of workers to stations in an assembly line, or one of its variants, and report a solution procedure. Balancing studies with a homogeneous workforce, workstation design studies without an assignment model, and works presenting no solution method were excluded.

Units of Analysis

The study does not involve human participants. Its units of analysis are of two classes and correspond to the two phases of the mixed design.

The first is the documentary corpus from which the requirements are derived: the studies included in the systematic review and the set of applicable standards, comprising ISO 9241-210 for the principles of user-centred design, ISO 21801-1 for cognitive accessibility and NOM-034-STPS-2016 for safety conditions in Mexican workplaces.

The second consists of 124 test instances built in accordance with the protocol of the four benchmark families of the problem: Roszieg, Heskia, Tonge and Wee-Mag, with 25, 28, 70 and 75 operations respectively. For each number of workers admitted by the family, the experimental design combines the two levels of dispersion across operators and the two levels of task-worker infeasibility defined by the protocol. Precedence graphs were calibrated to the order strength reported in the literature and generation seeds were fixed, so that any third party executing the procedure obtains the same figures.

Methodological Structure by Phases

The procedure is organised into four phases. Each pursues its own objective, relies on specific instruments and produces an identifiable result, so that the results section is structured into the corresponding subsections.

Phase 1. Systematic literature review. Its objective is to identify the methods applied to the problem between 2015 and 2026 and the treatment they give to uncertainty, in order to delimit the knowledge gap. It is executed in accordance with the PRISMA protocol described above. The result it produces is the state of the art and the selection flow diagram.

Phase 2. User-centred design and quality function deployment. Its objective is to obtain the hierarchy of technical requirements the design of the station must address. Needs are derived from documentary sources: Clauses 5 to 7 of ISO 21801-1, concerning motivation, comprehension and support for action; the disability profiles and personal rest allowances reported by Cais et al. (2025); the limits of perceived physical effort of Katiraee et al. (2023); and the task-worker compatibility constraints described by Araújo et al. (2015). Those needs are weighted on a scale of one to five and translated into technical requirements through the house of quality matrix, using the conventional scale of the method: nine for a strong relationship, three for moderate and one for weak. The priority of each requirement results from the sum of the products of the need's weight and the intensity of its relationship.

Phase 3. Characterisation of individual variability. Its objective is to establish the range of coefficients of variation with which the simulated workforce is parameterised. Unlike studies that assume those values without support, here they are taken from the range reported by the literature on human variability in manual assembly. The coefficient of variation is defined as the ratio of the standard deviation to the mean of the operation time, so that it expresses dispersion in relative terms and is comparable across operations of different duration.

Phase 4. Design and experimental evaluation of the algorithm. Its objective is to build the algorithm and determine whether incorporating dispersion improves line performance. The proposed method is a multi-start constructive heuristic with local search. The constructive phase distributes operations and workers among stations through priority rules based on positional weight, which jointly consider the expected time and its dispersion, with look-ahead checking so as not to exhaust the more flexible workers prematurely. The local search phase refines the solution by exchanging workers between stations and moving operations, verifying at each attempt that precedence relations are not broken; the minimum feasible cycle time is located through binary search. Evaluation is performed by Monte Carlo simulation with a lognormal distribution and three hundred runs per solution, through paired comparison instance by instance with 95 per cent confidence intervals. Since instances within a family operate on different time scales, results are reported in normalised form: each instance is compared against its own classical solution and what is averaged is the percentage change. The phase also includes a control test with a workforce of uniform coefficient of variation and a sensitivity analysis shifting the whole variability range.

Scope and Ethical Considerations

The scope of one methodological decision should be declared. Deriving the requirements from documentary sources is not equivalent to eliciting them directly from users: it captures what standards and the literature have recorded as needs of this population, but it does not incorporate the particularities of a specific workplace. Validation with users in the field is identified as future work.

As for ethical considerations, the study is entirely documentary and computational. It does not involve human participants or animals, collects no personal data of any kind and therefore did not require ethics committee approval.

RESULTS AND DISCUSSION

State of the Art and Identified Gap

The selection process identified 49 records: 6 in SciELO, 10 in Redalyc and 33 in the international open-access sources. Two were removed as duplicates, so that 47 proceeded to screening by title and abstract. Of these, 16 were discarded for not addressing the assignment of workers to stations or for reporting no solution procedure. Of the 31 reports sought for retrieval, 8 could not be obtained because the publisher restricts access to the full text, leaving 23 studies assessed at full text. Figure 1 presents the flow diagram of the process.

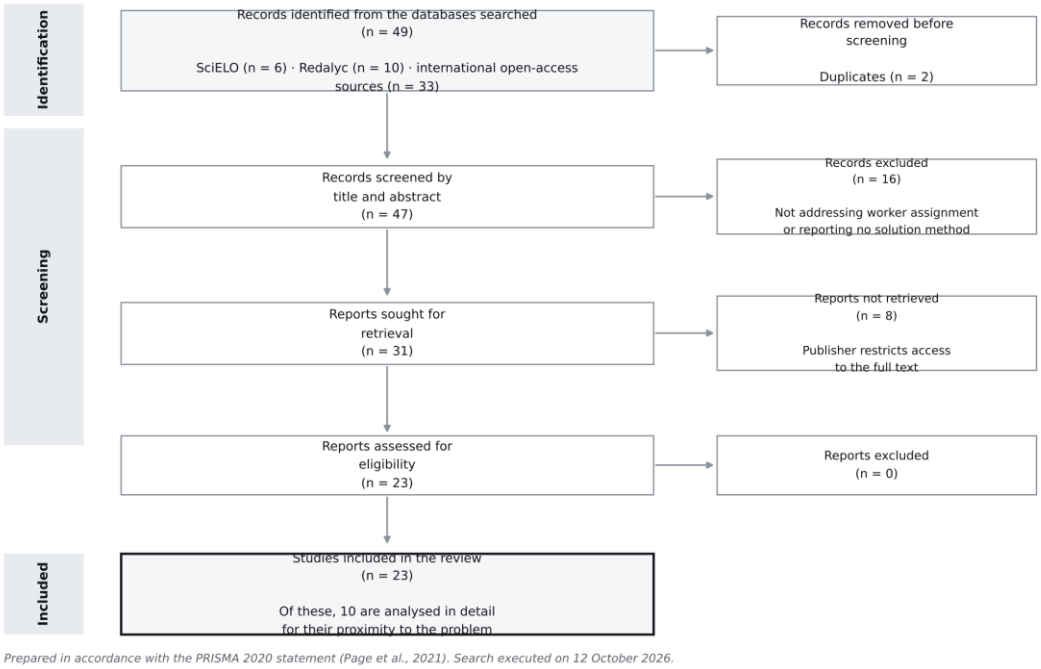


Figure 1: Flow diagram of the identification and selection of studies. Source: own elaboration in accordance with the PRISMA 2020 statement.

One finding of the process itself deserves recording. None of the 16 records retrieved from SciELO and Redalyc formulates the worker assignment and balancing problem with heterogeneous workers in the strict sense. Ibero-American open-access output on line balancing assumes homogeneous workforces, and the regional studies that do address disability approach it from the ergonomic design of the workstation, without an assignment model. The problem posed here is documented almost exclusively in international subscription journals, which limits its circulation in the region.

Table 2 gathers the ten studies closest to the problem posed, classified according to the treatment they give to uncertainty and their relation to the present work.

Table 2: Most relevant studies identified in the review

Authors and year	Main contribution	Treatment of uncertainty	Relation to the present work
Araújo, Costa and Miralles (2015)	Balancing of parallel lines with disabled workers	Not incorporated	Shares the study population; task-worker times are deterministic
Moreira, Cordeau, Costa and Laporte (2015)	Robust formulation of balancing with heterogeneous workers	Intervals with a per-worker robustness budget	The budget is set by the planner; it does not come from characterising each person's behaviour
Ritt, Costa and Miralles (2016)	ALWABP with stochastic worker availability	Two-stage stochastic programming over attendance	The random variable is whether the worker is present, not how much their time varies

Demirkol Akyol and Baykasoglu (2019)	Multiple-rule constructive randomised search for the ALWABP	Not incorporated	Direct methodological reference for the heuristic approach adopted
Yilmaz, O. F. (2020)	Robust optimisation for the U-shaped ALWABP	Combined interval and polyhedral set	Worst-case protection, not differentiated by each operator's regularity
Liu, Liu, Chu, Liu, Zheng and Chu (2022)	Risk-averse ALWABP with temporary and moving workers	Stochastic programming over the availability of disabled workers	Shares the population; uncertainty again falls on availability
Katiraee, Calzavara, Finco, Battaia and Battini (2023)	Balancing and assignment by expertise and perceived physical effort	Not incorporated; attributes treated deterministically	Antecedent with the richest individual attributes; none is temporal dispersion
Michels and Costa (2024)	Worker integration and balancing in multi-manned lines	Not incorporated	Combines a heterogeneous workforce and multi-manned stations, with fixed times
Cais, Culot, Scalera and Meneghetti (2025)	Human-robot collaborative balancing for the inclusion of disabled workers	Not incorporated	Models disability profiles and personal rest, but deterministically
Sahin (2026)	Balancing with moving workers and worker-dependent task times	Analyses dispersion levels of mean times across workers	Closest antecedent; the dispersion manipulated is between people, not that of each person with themselves

Source: own elaboration.

The classification makes the gap precise. Uncertainty has been incorporated along two routes — robust optimisation, which represents it through protection parameters set by the planner, and stochastic programming, which locates it in worker availability — while heterogeneity has been modelled as a difference between the means of different people. What has not been done is to characterise the dispersion of each person with respect to their own mean and to employ it as a criterion within the assignment decision. That is the space the present work occupies.

Hierarchy of Design Requirements

Applying quality function deployment to the needs derived from the documentary sources produced seven user needs and six technical requirements. Needs were weighted on a scale of one to five according to the relevance the sources attribute to them. Table 3 presents the needs with their weighting and documentary origin.

Table 3: User needs, weighting and documentary origin

User need	Weight	Source from which it is derived
Having enough time to complete the operation without pressure	5	ISO 21801-1, Clause 7 (planning and time management)
Keeping an own, sustainable pace throughout the shift	5	ISO 21801-1, Clause 7; Cais et al. (2025), personal rest
Clearly understanding what the operation involves	5	ISO 21801-1, Clause 6 (representation and understanding)
Being assigned an operation compatible with what the person can do	5	Araújo et al. (2015); Cais et al. (2025), compatibility matrix
Receiving support to complete the task when needed	4	ISO 21801-1, Clause 7; Katiraee et al. (2023), supporting role
Not exceeding tolerable physical effort	4	Katiraee et al. (2023), perceived physical effort
Keeping the assignment stable and predictable	3	ISO 21801-1, Clause 5 (managing attention)

Source: own elaboration from the cited sources.

The crossing of those needs with the technical requirements is presented in Figure 2, which reproduces the house of quality matrix with the weighting of each need, the intensity of its relationship with each requirement and the resulting priority.

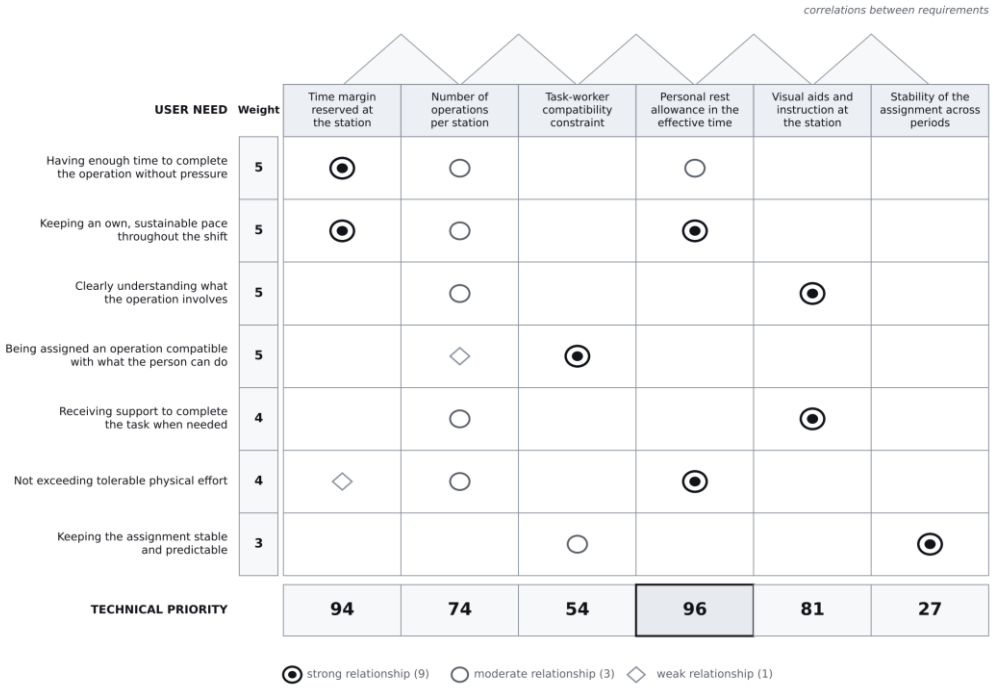


Figure 2: House of quality for the design of the inclusive workstation. Source: own elaboration.

The resulting hierarchy is summarised in Table 4.

Table 4: Technical priority of the design requirements

Technical requirement	Priority	Design mechanism
Personal rest allowance incorporated into the effective time	96	Time reservation
Time margin reserved at the station	94	Time reservation
Visual aids and instruction at the station	81	Communication
Number of operations per station	74	Load
Task-worker compatibility constraint	54	Feasibility
Stability of the assignment across periods	27	Predictability

Source: own elaboration.

The result admits a direct reading. The two highest-priority requirements, with 96 and 94 points, are both mechanisms of time reservation, and they stand clearly apart from the third. In other words, when the documented needs of this population are translated into design variables, the variable concentrating priority is how much time the plan reserves for each person.

That finding justifies the design decision this work adopts. The proposed algorithm acts precisely on the highest-priority requirement, and it does so differentially by operator, which is what the originating needs demand: not a uniform margin for the whole workforce, but one proportional to each person's regularity. It should be noted, however, that the hierarchy is derived from documentary sources and not from direct elicitation, so that it expresses what standards and the literature record as needs of this population.

Dispersion Profile of the Workforce

The parameterisation of the simulated workforce was established from the coefficient of variation values reported by the literature on human variability in manual assembly, which Table 5 gathers.

Table 5: Coefficient of variation values reported in the literature

Source	Coefficient of variation	Measurement context
Wang et al. (as cited in Malaki, 2012)	0.020 to 0.115	Walking-worker lines; deviation expressed as a percentage of the mean
De la Wayhe and Wild (as cited in Malaki, 2012)	0.10, 0.20 and 0.30	Unpaced lines, normal distribution
El-Rayah (as cited in Malaki, 2012)	0.15 and 0.30	Unpaced lines
Malaki (2012)	0.05, 0.20 and 0.40	Assigned by operator skill level: high, moderate and low
Carnall and Wild (as cited in Malaki, 2012)	0.50	Unpaced lines

Source: own elaboration from the cited sources.

Two observations follow from the table. The first is that the documented range is wide, spanning from values close to 0.02 up to 0.50, which confirms that operation time variability is not a marginal phenomenon. The second, and more pertinent for this work, is that Malaki (2012) assigns different coefficients according to the operator's skill level, with 0.05 for the high-skill worker, 0.20 for the moderate and 0.40 for the low-skill one. That structure, in which people within the same workforce exhibit dispersions differing by a factor of eight, is exactly the heterogeneity assumption on which the proposed method rests, and it comes from the literature rather than from an assumption by the authors.

Drawing on that range, the parameterisation of the instances assigns each worker one of four levels of individual dispersion: 0.05, 0.10, 0.20 and 0.35. The first two coincide with the values reported by Malaki (2012) and by De la Wayhe and Wild for operators of high and moderate regularity, and the highest lies below the documented maximum. It should be noted that the primary sources correspond to studies of unpaced and walking-worker lines in the general population, not to measurements taken on workers with cognitive disabilities. No study was located that has measured the coefficient of variation of operation time by disability type in manufacturing, which constitutes a measurement gap in itself.

Comparative Performance of the Methods

The experimental evaluation compared the proposed method, with k equal to one, against the classical method, which the algorithm itself reproduces with k equal to zero. The comparison is paired: both methods solved exactly the same 124 instances with the same program, modifying a single parameter. Over the complete set, the proportion of cycles meeting the committed time rose from 9.9 to 79.4 per cent.

Expressed as a paired difference, compliance rises by 69.6 percentage points, with a 95 per cent confidence interval of 67.1 to 72.0 points. The improvement is not an average concealing exceptions: all 124 instances favour the proposed method, so a sign test rejects the hypothesis of no difference at any conventional level. The dispersion of the cycle time falls by 38.7 per cent on average, with an interval of 34.9 to 42.5 per cent. The mean simulated cycle time, by contrast, varies by 1.5 per cent with an interval of −0.4 to 3.4 per cent that contains zero. The cost of the method therefore falls on the committed time the plan announces, which necessarily rises with the margin, and not to any detectable degree on the time the line actually realises.

The breakdown by family, presented in Table 6, reveals that this improvement is not uniformly distributed.

Table 6: Results with k = 1 over the four benchmark families

Family	Operations	Compliance, classical method	Compliance, proposed method	Reduction in variation
Roszieg	25	22.7 %	91.3 %	−37 %
Heskia	28	17.1 %	89.1 %	−29 %
Tonge	70	0.7 %	69.6 %	−45 %
Wee-Mag	75	0.6 %	69.1 %	−43 %

Source: own elaboration.

The first result is the increase in reliability. In all four families the proposed method substantially raises the proportion of cycles meeting the committed time, and does so while reducing performance variation by between 29 and 45 per cent. The line does not merely comply more often: it becomes more predictable.

The second result was not anticipated and delimits the scope of the method: the benefit grows with the size of the line. In Roszieg and Heskia, of 25 and 28 operations, the classical method complies in 22.7 and 17.1 per cent of cycles; in Tonge and Wee-Mag, of 70 and 75 operations, it complies in 0.7 and 0.6 per cent. The explanation lies in the fact that variability accumulates along the line: the more stations are chained, the greater the probability that one of them exceeds the promised time and drags the whole cycle with it. Since real industrial lines approach the size of the larger families, the scenario in which the classical method almost always fails is also the most frequent in practice.

An initial explanation attributed that behaviour to the precedence structure, measured by order strength. The data from the four families do not support it: Heskia and Wee-Mag exhibit an almost identical order strength, of 0.22 and 0.23, and behave differently, whereas Wee-Mag resembles Tonge, whose order strength is 0.59. The variable that orders the results is the size of the line, not the density of the precedences.

The third result concerns the cost of the method. The increase in margin is paid for with a higher nominal cycle time, and that cost does not grow indefinitely without consequence. With a value of two deviations the cycle time deteriorates by between 7 and 10 per cent and the improvement in the tail of the distribution vanishes, because the algorithm reserves so much slack for the irregular workers that it ends up overloading the consistent ones and unbalancing the line. There is, therefore, a point of equilibrium, and exceeding it proves counterproductive.

A final observation concerns computational cost. In its present single-threaded Python implementation, the complete procedure, multi-start construction followed by local search, resolves an instance in a median of 0.38 seconds, with a mean of 0.52 and a maximum of 2.18 seconds over the 496 solutions generated for this experiment, the largest corresponding to the family of 75 operations. Incorporating dispersion into the assignment criterion therefore carries a negligible cost for planning purposes, which is relevant because a line is rebalanced when the product mix or the composition of the workforce changes and not continuously.

Selection and Calibration of the Margin Parameter

The margin parameter admits a direct reading, and that is what makes it operable. It multiplies each worker's own standard deviation, so that the effective time with which the algorithm plans is the mean time of the worker plus k times their deviation. A value of zero reproduces the classical method exactly rather than approximately: the effective time collapses to the mean and the procedure returns the same assignment as positional-weight balancing on mean times. That identity is what allows the parameter to be read as a dial between the classical method and increasingly conservative plans, and it is also what makes the paired comparison legitimate, since both arms are produced by the same program.

The parameter was explored over the values zero, one half, one and one and a half, with an additional examination at two. The value of one was adopted for the main comparison because it carries a transparent operational meaning, one standard deviation of the individual worker, and because it already captures the greater part of the available gain. The behaviour across the range is asymmetric: compliance rises steeply between zero and one and then flattens, whereas the cost in nominal cycle time continues to grow. At two deviations the cycle time deteriorates by between 7 and 10 per cent and the improvement in the tail vanishes, because so much slack is reserved for the irregular workers that the consistent ones become overloaded and the line unbalances.

For practical use the parameter need not be guessed. The procedure a planner would follow is to run the algorithm over increasing values of k and retain the smallest value that reaches the compliance target to which the line is committed, which bounds the cost paid in cycle time to the minimum necessary. Where no explicit target exists, a value of one is a reasonable starting point, and values above two are not advisable on the evidence reported here. The calibration is local in a further sense: because k multiplies each worker's own deviation, the same value produces a small margin in a consistent workforce and a large one in a variable workforce, so the parameter does not require retuning when the composition of the line changes.

Control Test and Sensitivity Analysis

To verify that the advantage stems from heterogeneity between workers and not simply from having added slack to the plan, the experiment was repeated with a workforce in which all operators share the same coefficient of variation. In that control scenario the proposed algorithm produces exactly the same assignment as the classical one, and the difference is 0.00 per cent. The mechanism therefore operates for the reason the hypothesis predicts: when the margin is added in the same proportion to everyone, the relative ordering between workers does not change, and neither does the assignment decision.

That result rules out the most serious alternative explanation that could be raised against the method, namely that any uniform increase in slack would produce the same effect. It does not. Table 7 additionally presents the sensitivity analysis, which repeats the experiment shifting the whole variability range of the workforce.

Table 7: Sensitivity analysis, 31 instances per scenario

Scenario	Improvement in the worst 5 % of cycles	Reduction in variation
Highly consistent workforce	−1.3 %	−23 %
Baseline workforce	−4.8 %	−32 %
Highly variable workforce	−4.3 %	−28 %
Control: uniform coefficient of variation	0.00 %	0.0 %

Source: own elaboration.

The advantage holds in the three variability scenarios, with improvements in the worst five per cent of cycles of between 1.3 and 4.8 per cent and reductions in variation of between 23 and 32 per cent. The conclusions therefore do not depend on the particular values adopted within the documented range. The control row differs from the preceding ones not in magnitude but in nature: it is not one more sensitivity scenario but the condition under which the method ceases to contribute, and its exactly null value is what allows the advantage to be attributed to heterogeneity between people.

DISCUSSION

The results allow the contribution to be situated against the reviewed literature. Moreira et al. (2015) and Yılmaz (2020) protect the line against uncertainty through parameters the planner establishes; the method proposed here derives that protection from each worker's documented regularity, so that slack ceases to be an administrative decision and becomes a consequence of the workforce profile. Ritt et al. (2016) and Liu et al.

(2022) model the randomness of attendance; this work models it in the duration of the task, which is a distinct and complementary dimension.

With respect to Şahin (2026), the closest antecedent, the difference is twofold. The first concerns the object: what that work manipulates is the dispersion of mean times across different workers, whereas here what is modelled is the dispersion of each person with respect to their own mean over successive repetitions. The second concerns the function: there dispersion operates as a factor of the experimental design, whose effect is measured, whereas here it operates as a criterion within the assignment procedure, determining which station receives whom and with how much margin. The control test allows precisely that second difference to be verified.

From the perspective of user-centred design, the QFD result contributes an element the technical literature does not usually incorporate: the variable on which the algorithm acts was not chosen for methodological convenience but because it concentrated the highest priority when the documented needs of the population were translated into technical requirements. The consistency between the highest-priority requirement and the mechanism of the algorithm is not accidental, yet neither was it imposed: the hierarchy was computed from the weighting of the needs, not the other way round.

Finally, the finding on line size carries practical implications worth underlining. If the benefit of the method grows with the number of operations, and real lines fall within the range of the larger families, then the scenario in which conventional balancing proves least reliable is also the one that predominates in industry. For a workplace employing people with disabilities, that combination is precisely what produces the non-compliance later attributed, mistakenly, to the people.

LIMITATIONS

The evaluation is entirely computational. The method has not been applied to a line in operation, so what is reported here is its behaviour under the standard experimental protocol of the field and not its performance in a particular plant.

Design requirements were derived from normative and literature sources, not from direct elicitation with users. The hierarchy obtained expresses what standards and studies record as needs of this population, but it does not incorporate the particularities of a specific workplace nor the voice of individual workers.

The coefficients of variation come from studies of human variability in manual assembly conducted on the general population. No measurement was located of the coefficient of variation of operation time by disability type in manufacturing, so that the magnitude of dispersion in this population remains unestablished, although the sensitivity analysis shows the conclusions hold over a wide range.

The test instances are not the original benchmark instances, which are not publicly available, but instances built in accordance with the protocol described in the literature. Precedence graphs were calibrated to the reported order strength, yet validation on the original instances remains desirable.

Lastly, the comparison was made against the classical method within the same program and not against published heuristics. The result supports the claim that considering dispersion improves upon the classical method, not that the proposed algorithm outperforms the state of the art; these are distinct claims and only the first is defended here. The runtimes reported above describe the cost of the procedure in absolute terms and likewise do not constitute a comparison of computational efficiency against those heuristics.

CONCLUSION

This work identified and modelled a dimension of the worker assignment and balancing problem that the literature had left outside the decision criterion. Models with heterogeneous workers represent each person by their mean time and, in so doing, treat as equivalent two operators who are not equivalent in daily operation. Incorporating individual performance dispersion substantively modifies the quality of the resulting assignment.

That conceptual contribution materialises in four results. The first is the delimitation of the gap through systematic review: uncertainty has been modelled over the system or over attendance, heterogeneity as a difference between the means of different people, and individual attributes deterministically, but the dispersion of each person with respect to themselves had not been employed as an assignment criterion. The second is the hierarchy of requirements obtained through quality function deployment, in which time reservation concentrated the highest priority when the documented needs of the population were translated into design variables.

The third is the quantification of the trade-off the method offers: in exchange for a somewhat higher nominal cycle time, the line delivers on its promise in close to eight out of ten cycles instead of one, and its performance becomes between 29 and 45 per cent more stable. The fourth, not initially sought, is the evidence that the benefit grows with the size of the line, which makes the method more useful precisely in the long lines that predominate in practice.

To this is added a result of a methodological order. The control test, in which a workforce of uniform coefficient of variation yields an exactly null difference, establishes not only that the method works but why it works, and delimits the condition under which it ceases to do so. The advantage stems from differences between people and not from having added slack to the plan.

The agenda that follows is ordered by priority. In the short term, to compare the procedure against published heuristics and to submit it to the original benchmark instances. In the medium term, to elicit requirements directly from workers with cognitive disabilities and their support persons, in accordance with the process ISO 9241-210 describes, and to measure the coefficient of variation of operation time in a real workplace. That measurement, today absent from the international literature, would in itself constitute a contribution to the field and would turn the principal assumption of this work into a datum.

Ethical Approval

This study did not involve human participants or animals and therefore did not require ethical approval. It is entirely documentary and computational, and no personal data were collected.

Conflict Of Interest

The authors declare that they have no conflict of interest.

Data Availability

The source code of the algorithm, the instance generator and the simulation scripts are publicly available at https://github.com/l23201024-tech/ALWABP-HEUR-STICO. The repository contains the priority rules, the local search, the Monte Carlo routine and the experimental driver that produces the tables reported here. Instance generation and simulation both use fixed seeds, so that execution of the procedure reproduces the figures of this article exactly. The simulation settings are those stated in the methodology: lognormal operation times, three hundred replications per solution, and the coefficients of variation 0.05, 0.10, 0.20 and 0.35 assigned across the workforce.

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