This document contains supplementary material related to the article:

García-Manglano, S., Maheut, J., García-Sabater, J. J. & Ruiz, A. (2026). Systematic literature review on the impact of multifunctional training on organizational resilience. *Management Letters / Cuadernos de Gestión*, 26(1). https://doi.org/10.5295/252468jm

Appendix 1. Search filters

Block 1 (organisational setting): TI-ABS-KEY (work* OR organi?ation* OR compan* OR corporate* OR firm* OR business* OR employ* OR personnel OR staff* OR workforce* OR labor OR labour OR team* OR manager* OR leader*)

Block 2 (resilience/adaptability): TI-ABS-KEY [(organi?ation* OR company* OR workforce* OR team* OR labor OR labour) NEAR/3 (adaptabil* OR flexibil* OR resilien* OR agilit* OR robust*) OR "organizational resilience" OR "organizational flexibility" OR "organizational adaptability" OR "organizational agility" OR "workforce flexibility" OR "labor flexibility" OR "labour flexibility" OR "functional flexibility" OR "workforce agility"]

Block 3 (MT / cross-training): TI-ABS-KEY (polivalen* OR multiskill* OR multi-skill* OR "multi*skill*" OR "multi functional" OR "multi-functional" OR "multifunctional" OR versatil* OR "job rotation" OR "cross-training" OR crosstrain* OR “cross-train*” OR "cross utilization" OR "cross-utilization" OR "cross functional" OR "polyvalent" OR "multi-competenc*" OR upskill* OR reskill* OR "multi-skilled" OR staffing OR "personnel scheduling" OR "workforce scheduling")

Negative filter: AND NOT (psychologic OR mental OR harass OR mindfulness OR burnout OR e-learning OR elearning OR online

Appendix 2. Full classification of all 87 studies (including sector, method, U/H codes, and resilience proxies)

Article	Sector (as stated in the article)	Method (coding + detail)	U (0–3)	Uncertainty type incorporated	H (0–3)	Human-factor type incorporated	Resilience proxy metric(s) used
(Felan et al., 1993) Labour flexibility and staffing levels in a dual-resource constrained job shop	Manufacturing – job shop (dual-resource constrained; hypothetical model)	SIM (discrete-event simulation): comparison of cross-training strategies versus increasing staffing levels in a simulated DRC job shop	U2	Job-shop variability through DES; order interarrival and processing times treated as not controllable (stochastic shop dynamics)	H0	Skill matrix / cross-training as structural capacity only	Mean flow time (WIP proxy), labour utilisation, mean tardiness, % jobs tardy
(Slomp & Molleman, 2002) Cross-training policies and team performance	Not industry-specific (generic teams/operations with order mix and absenteeism)	ANA/COMP: analytical study with an assignment heuristic to compare cross-training policies under absenteeism and order-mix variation	U2	Absenteeism (no one absent vs one absent) + demand fluctuation in order mix (uniform ±40)	H1	Coordination effort + skill-use patterns (cross-training policy impacts)	Bottleneck-worker load, coordination effort, number of newly used qualifications
(Sawhney, 2013) Implementing labor flexibility: A missing link between acquired labor flexibility and plant performance	Manufacturing – printed circuit board (PCB) assembly plants	EMP-MIX: case studies + survey; quantitative analysis (PLS) to test relationships between acquired/implemented flexibility and plant performance	U1	Volatility discussed (temporary bottlenecks/overloads) but not modelled probabilistically	H1	Implementation sophistication; behavioural/technical side effects of flexibility implementation	Plant performance measured via WIP and manufacturing cost (self-reported relative to competitors)
(Felan & Fry, 2001) Multi-level heterogeneous worker flexibility in a Dual Resource Constrained (DRC) job-shop	Manufacturing – DRC job shop (fabrication + assembly; heterogeneous workers)	SIM (simulation study): evaluates cross-training levels considering heterogeneity and operational effects (e.g., workload imbalance) in a simulated DRC job shop	U2	Explicit stochastic arrivals (Poisson job arrivals), random product selection / shop variability in simulation	H1	Worker heterogeneity in proficiency + multilevel flexibility structures	Mean tardiness, % jobs tardy, total inventory, labour variance (training cost proxy) + other cost surrogates
(Hopp & Oyen, 2004) Agile workforce evaluation: a framework for cross-training and coordination	General (manufacturing/service operations): evaluation approach applicable across contexts	CONC/FRAME: conceptual evaluation framework grounded in prior literature and illustrative industrial cases to assess cross-training and coordination	U1*	Variability and congestion mechanisms discussed (mean/variance of cycle time, waiting times); formal stochastic modelling is not consistently extractable as a full model from the text	H1	Coordination + cross-training strategy mechanisms	Mean/variance of cycle time / lead time (responsiveness), delivery reliability, quality impacts (as discussed in the framework)
(Grant & Hallam, 2016) Team performance in a lean manufacturing operation: it takes the will and a way to succeed	Manufacturing – electronics assembly plant (lean/pull system)	EMP-LONG: longitudinal field study following five multifunctional teams during pull implementation; analysis linking team characteristics to performance metrics	U0	No explicit modelling of uncertainty	H1	Team collaboration, team flexibility, shared priorities (behavioural/team factors)	Schedule performance, product quality, labour efficiency

(Fraser & Hvolby, 2010) Effective teamworking: can functional flexibility act as an enhancing factor? An Australian case study	Manufacturing – cellular manufacturing (Australia)	EMP-CASE(QUAN): case study with an IPO-model-based questionnaire; quantitative tests of the effects of rotation/flexibility on team processes and performance	U0	No explicit modelling of uncertainty	H1	Job rotation / functional flexibility as team input affecting processes	Team performance (survey output construct) + team process measures (communication, conflict resolution, etc.)
(Hopp et al., 2004) Benefits of skill chaining in serial production lines with cross-trained workers	Manufacturing – serial production lines (CONWIP)	ANA + SIM: modelling (MDP/Markov in the theoretical framework) plus numerical/simulation evaluation (for non-exponential distributions), comparing skill chaining with alternatives	U3	Short-term operational variability explicitly treated; focus on stochastic line behaviour (Little's law / WIP–throughput relationship)	H1	Skill chaining structures (strategic skill design)	Throughput, inventory/WIP, cycle time; WIP-to-throughput ratio as efficiency/resilience proxy
(McCreery & Krajewski, 1999) Improving performance using workforce flexibility in an assembly environment with learning and forgetting effects	Manufacturing – assembly environment (assemble-to-order; line profile by variety and task complexity)	SIM (discrete-event simulation): cross-training and dynamic deployment decisions with learning/forgetting; explicit simulation methodology (batch means, Welch procedure, etc.)	U2	DES captures variability in assembly environment and job/system dynamics	H2	Learning and forgetting dynamics explicitly modelled	Throughput (standard work content), WIP, labour utilisation, labour efficiency
(Slomp & Suresh, 2005) The shift team formation problem in multi-shift manufacturing operations	Manufacturing – multi-shift operations (case in a Dutch manufacturing company)	OPT (goal programming) + procedure: goal programming formulation and a two-phase procedure to assign operators to shift teams under multiple objectives	U0	Deterministic (goal programming formulation)	H0	Skills and team formation constraints (no dynamic human effects)	Goal attainment balancing labour flexibility and labour-related costs (multi-objective)
(Jordan et al., 2004) Chained cross-training of workers for robust performance	Manufacturing (maintenance operations in an automotive assembly context)	ANL: stochastic/queueing model + numerical evaluation (analytical modelling of cross-training "skill chaining")	U3	Formal stochastic queueing assumptions (random arrivals/service) underpin robustness evaluation	H1	Skill chaining + heterogeneous task/service characteristics	Mean time in system / response time (incl. queueing time), utilisation and robustness of those measures
(Julie Yazici, 2005) Influence of flexibilities on manufacturing cells for faster delivery using simulation	Manufacturing (manufacturing cells / delivery lead time context)	SIM: discrete-event simulation study (simulation used to assess flexibility impact)	U2	Volatile demand explicitly stated; evaluated via DES scenarios	H0	Labour flexibility as redeployable capacity only	Lead time / delivery speed, resource utilisation
(Azizi & Liang, 2013) An integrated approach to worker assignment,	Manufacturing (general production environment)	OPT+HEU: mathematical programming model (assignment	U1	Demand/labour fluctuations discussed as motivation; model	H2	Task rotation as decision variable + productivity loss	Total cost (training + flexibility + productivity-loss), feasibility of

workforce flexibility acquisition, and task rotation		+ training + rotation) + constructive-search heuristic		uses time-phased planning inputs (not probabilistic)		cost + training schedule	assignment/rotation plan over horizon
(McCreery et al., 2004) Performance implications of assembly work teams	Manufacturing (manually-paced assembly area)	SIM: discrete-event simulation (SLAM II) + experimental analysis	U2	System “in flux” and multiple environment types simulated (variety/complexity conditions)	H2	Learning/forgetting effects explicitly discussed; team configuration and task sharing	Throughput (WORK definition), worker productivity/efficiency indicators (plus performance sensitivity to variety/complexity)
(Kim & Nembhard, 2010) Cross-trained staffing levels with heterogeneous learning/forgetting	Manufacturing / production systems (parallel DRC systems; sector no aplicado a una industria concreta)	SIM: simulation-based experimentation + ANOVA (learning/forgetting heterogeneity; staffing level as response)	U2	System dynamics evaluated via experimentation/simulation logic to meet production requirements (stochastic system context)	H2	Heterogeneous learning/forgetting among workers explicitly modelled	Minimum staffing level required to meet production requirement; productivity/throughput outcomes
(Park, 1991) The examination of worker cross-training in a dual resource constrained job shop	Manufacturing (dual resource constrained job shop)	SIM: discrete-event simulation (SLAM) varying cross-training matrices	U2	stochastic DES (random shop dynamics)	H0	skill matrix only	Flow time / WIP / tardiness-type measures and related shop performance indicators
(Henao et al., 2015) The impact of multi-skilling on personnel scheduling in the service sector: a retail industry case	Service (retail)	OPT: mixed-integer linear programming model (training decisions + assignment/scheduling over planning horizon)	U0	deterministic model (explicitly excludes demand uncertainty and unplanned absences)	H1	productivity/skill-related heterogeneity represented through parameters	Total cost + understaffing/coverage as service level proxy
(Van Oyen et al., 2001) Performance opportunity for workforce agility in collaborative and noncollaborative work systems	Manufacturing (serial production systems)	ANL: analytical queueing/stochastic models (sample-path results; policy comparison; includes collaborative vs noncollaborative assumptions)	U3	formal stochastic/queueing modelling	H1	collaboration vs non-collaboration structure (work organisation affects outcomes)	WIP / cycle time / throughput-type system performance indicators
(Porto et al., 2022) Solving a staffing problem with annualized hours, multiskilling with 2-chaining, and overtime: A retail industry case	Retail (real case using data from a Chilean retailer)	OPT (MILP): proposes a mixed-integer linear programming model to determine workforce size, the multiskilling plan (2-chaining), and weekly allocation of regular and overtime hours; validated through	U1	Uncertainty is handled through deterministic scenario/parametric variation of demand: different demand profiles (seasonality) and demand-variability levels (coefficients of variation, e.g., CV 10%, 20%, 30%) are tested to evaluate the flexibility strategy, but	H0	MT is operationalised as structural multiskilling under a 2-chaining design (employees trained to perform up to two task types	Demand coverage / service continuity proxies: near 100% demand coverage, over/understaffing ≈ 0% under tested profiles/variability; plus total cost savings vs

		experiments/scenarios using real and simulated case data		uncertainty is not explicitly incorporated in the MILP formulation (the paper flags this as future work)		forming closed chains) combined with annualised hours and overtime; no learning/fatigue/behavioural dynamics are modelled	single/double flexibility strategies; reporting also includes staffing and flexibility indicators (e.g., % multiskilled employees, % total multiskilling, and % coverage via overtime)
(Porto et al., 2025) Improving the robustness of retail workforce management with a labor flexibility strategy and consideration of demand uncertainty	Retail / retail services (personnel scheduling problem in a retail setting)	OPT (two-stage stochastic programming): develops a two-stage stochastic model to size the workforce, define the training plan (2-chaining), and allocate weekly regular and overtime hours while explicitly accounting for demand variability/uncertainty; compared against a deterministic model and evaluated through case experiments	U3	two-stage stochastic programming (explicit demand uncertainty)	H0	skills/training structure only (2-chaining)	Expected labour cost components (over/understaffing, wages, training) and robustness comparison vs deterministic solution
(Olivella & Nembhard, 2017) Cross-training policies for team cost and robustness	Service operations (generic work-team service system) addressing demand-mix variation and absenteeism	SIM: simulation-based assessment of alternative cross-training policies, explicitly evaluating cost and robustness under demand-mix variability and absenteeism	U2	simulation under demand-mix bounds + absenteeism	H0	skill matrix only	Cross-training cost + unmet demand (within demand bounds) + unmet demand due to absenteeism (robustness definition)
(Tiwari & Roy, 2002) Application of an evolutionary fuzzy system for the estimation of workforce deployment and cross-training in an assembly environment	Manufacturing – assembly environment	COMP/AI: evolutionary fuzzy expert system (fuzzy rule-based model enhanced via evolutionary search) to estimate workforce deployment and cross-training; validated through computational experiments/illustrative example	U0 –	no explicit stochastic uncertainty (fuzzy logic handles vagueness, not operational volatility)	H0	no human dynamics beyond skills	Estimation accuracy/fitness; recommended cross-training amount and deployment policy (not operational resilience metrics)
(Mou & Robb, 2019) Real-Time labour allocation in grocery stores: a simulation-based approach	Retail – grocery stores	SIM (DES): discrete-event simulation–based decision support (retail store simulator) to evaluate real-time labour allocation policies; scenario analysis on staffing/understaffing outcomes	U2	simulation capturing variability in customer needs/demand and staffing mismatches	H1	skill range and proficiency as operational attributes	Service level / market share and operational performance under understaffing and reallocation rules

(Porto et al., 2019) Hybrid flexibility strategy on personnel scheduling: Retail case study	Retail	OPT (MILP): mixed-integer linear programming model for personnel scheduling combining flexibility mechanisms (incl. multiskilling); evaluated through computational experiments/scenarios in a retail case	U1	demand variability handled through deterministic scenarios (no stochastic program)	H1	flexibility via multiskilling + contract structure (static)	Labour cost + demand coverage / service quality proxy (under/overstaffing outcomes)
(Iravani & Krishnamurthy, 2007) Workforce agility in repair and maintenance environments	Repair & maintenance operations (machine-repair/maintenance setting)	ANA (Markov/queueing policy model): analytical modelling of partially cross-trained repair crews (policy characterisation + numerical study), including comparison with heuristic policies	U3	Markov/queueing policy model	H0	skill matrix only	Total average machine downtime + repairman cost (explicit performance measures)
(Gnanlet & Gilland, 2014) Impact of productivity on cross-training configurations and optimal staffing decisions in hospitals	Healthcare – hospitals (cross-training of nursing staff across units)	ANA/OPT: queueing-theoretic modelling + optimisation/numerical analysis to compare cross-training configurations (e.g., chaining) and staffing decisions under productivity effects	U3	two-stage stochastic model (uncertain demand)	H1	productivity assumptions for cross-trained staff influence outcomes	Labour cost and demand coverage (e.g., staffing levels, outsourcing/contract usage)
(J. A. Bokhorst et al., 2004) Development and evaluation of cross-training policies for manufacturing teams	Manufacturing – dual resource constrained (DRC) systems / manufacturing teams	OPT + SIM: development of cross-training policies using an integer goal programming formulation, followed by simulation study to evaluate policy performance	U2	simulation used to evaluate policies under stochastic system behaviour	H0	skills only	Mean flow time + standard deviation of workload distribution (robustness/variability proxy)
(Yang et al., 2007) An evaluation of worker cross training and flexible workdays in job shops	Manufacturing – job shops	SIM: simulation-based experimental evaluation of cross-training and flexible workday policies (including experiments under different workload variability conditions)	U2	stochastic simulation (job shop dynamics + workload variability experiments)	H0	skills only	Mean tardiness + mean WIP (explicitly defined as key performance measures)
(Altendorfer et al., 2021) Service level improvement due to worker cross training with stochastic worker absence	Manufacturing – production system (service level under worker absence)	SIM-OPT (GA): simulation-based optimisation of worker skill dedication under stochastic worker absence, using a genetic algorithm; followed by simulation study and numerical results	U2	stochastic worker absence integrated in simulation/optimisation	H0	skills only	Service level as primary resilience proxy + training level/skill dedication indicators

(Turan et al., 2021) A multi-skilled workforce optimisation in maintenance logistics networks by multi-thread simulated annealing algorithms	Maintenance logistics networks	META (MTSA): optimisation model solved via a multi-thread simulated annealing metaheuristic (two-stage iterative heuristic framework) + numerical study/benchmarking	U3	stochastic failures and repair processes (explicit random failures, exponential repair times)	H0	skills only	Total cost components combining workforce/inventory/backorder-type costs; network performance under random failures
(Wise et al., 2020) Clarifying workforce flexibility from a division of labor perspective: a mixed methods study of an emergency department team	Healthcare – emergency department (Fast Track), Sydney (Australia)	EMP-MIX (sequential mixed methods): observational time–motion study of task distribution across roles + follow-up qualitative component to explain mechanisms/conditions enabling flexibility	U1	Variability/unpredictability of clinical work (discussed; not probabilistically modelled)	H2	Coordination/work organization and task reassignment (flexibility as a socio-technical phenomenon, not only a "skill matrix")	Proxy measures of flexibility/coverage (e.g., overlap of roles/tasks; ability to cover activities), plus qualitative findings on adaptation
(Suresh & Slomp, 2005) Performance comparison of virtual cellular manufacturing with functional and cellular layouts in DRC settings	Manufacturing – DRC (dual-resource constrained) settings; job-shop/cellular manufacturing layouts	SIM: simulation-based experimental comparison of virtual cellular manufacturing vs functional and physical cellular layouts, varying labour flexibility and related operational factors	U1	"Uncertainty" treated as parametric variation/scenarios (no explicit stochasticity in the accessible abstract)	H0	Labor flexibility as structural capacity (levels of flexibility + rules)	Comparative layout performance under scenarios (specific metrics not detailed in the accessible abstract)
(Daniels et al., 2004) Flow shop scheduling with partial resource flexibility	Manufacturing – flow shop scheduling with partially flexible labour/resources	ANA/OPT (scheduling theory + mathematical programming + heuristics): formal problem definition with mathematical programming formulation; complexity discussion (NP-hardness) and heuristic/exact solution procedures for partial resource flexibility structures	U2	Stochastic system dynamics (control/queueing-type modelling; steady-state performance)	H0	Flexibility as resource assignment (no explicit human behaviour)	Profit (revenues) vs staffing costs; comparison of marginal returns to capacity/flexibility
(Stewart et al., 1994) Mathematical models for developing a flexible workforce	Manufacturing – production environments (general)	OPT: mathematical programming models (with integer/binary decisions) to plan workforce flexibility development; includes modelling of training/flexibility decisions and computational evaluation/illustration	U1	Requirements linked to a planned production program (uncertainty not specified as stochastic/robust in the accessible excerpt)	H0	Cross-training as capacity (who to train/how much)	Cross-training plan/fit to medium-range needs; specific operational objective metrics not visible in the accessible excerpt
(Cuevas et al., 2016) A mixed integer programming approach	Service sector – customer-facing multi-activity	OPT (MIP): mixed-integer programming model for short-term multi-skilled tour/shift scheduling (design shifts/days off	U0	No explicit uncertainty (deterministic formulation in the abstract)	H1	Heterogeneity via skill levels (no explicit behaviour/learning)	Coverage of work requirements; balance of coverage ratios (coverage quality)

to multi-skilled workforce scheduling	workforce (generic service setting)	+ assign activities + assign employees), solved computationally					
(Gel et al., 2007) Hierarchical cross-training in work-in-process-constrained systems	Manufacturing/service operations – WIP-constrained flowlines (pull/CONWIP systems); examples include manufacturing flowlines and service settings with hierarchical skills	ANA/MDP: analytical modelling of CONWIP flowlines with partially cross-trained workers and hierarchical skill sets; optimal policy characterization for general stochastic processing times (fixed-before-shared principle), closed-form throughput for exponential times via Markov analysis, and extension/illustration including floater worker cases (solved via an MDP/value-iteration approach for exponential settings)	U2	Variability in the production system (typical analytical queueing/line framework under WIP constraints)	H0	Hierarchical skill structure (no behavioural human factors)	Throughput (and performance associated with the cross-training/CONWIP policy)
(Easton, 2011) Cross-training performance in flexible labor scheduling environments	Service operations – extended-hour, multi-department labour scheduling (generic)	OPT (two-stage stochastic) + SIM: two-stage stochastic staffing/cross-training/scheduling/allocation model under uncertain demand and attendance, followed by simulation to evaluate cost/service outcomes	U2	Variation in workloads/scheduling environment (simulation used to capture variability)	H1	Implicit coordination cost / organizational impact of cross-training	Total labor cost and unmet demand (service level)
(Chen et al., 2024) Technician routing and scheduling with employees' learning through implicit cross-training strategy	Service operations – field service/technician routing and scheduling	ANA/COMP (MDP + ADP heuristic): Markov decision process formulation; approximate dynamic programming / cost function approximation algorithm with a two-phase routing–scheduling heuristic; extensive computational experiments	U0	No exogenous uncertainty stated (optimisation model with learning)	H2	Learning/skill acquisition (implicit cross-training) and its impact on productivity/costs	Total cost (routing + service times) and learning/cross-training benefits
(Olivella & Nembhard, 2016) Calibrating cross-training to meet demand mix variation and employee absence	Manufacturing/production planning – work team cross-training under demand-mix variation and absences	OPT (scenario-based mathematical programming): model with binary training/skill decisions designed to ensure feasibility across demand and absence scenarios; calibration-	U3	Demand-mix variation controlled via bounds/maximum processing times per product + requirement to remain feasible under absences	H0	Cross-training as a set of qualifications; no behavioural component	Operational feasibility/robustness under mix + absences; size/configuration of the cross-training set

		oriented approach with numerical analysis					
(Mou, 2022) Integrated order picking and multi-skilled picker scheduling in omni-channel retail stores	Retail – omni-channel stores (order picking + multi-skilled pickers)	OPT (MIP + decomposition/CG) + COMP: integrated mixed-integer model for picking and multi-skilled picker scheduling; solved via algorithmic approach (incl. decomposition/column generation) and computational experiments	U1	Experiments varying order size and heterogeneity; no explicit probabilistic uncertainty model in the abstract	H1	Heterogeneous/multi-skilled workforce (picker differences treated as parameters)	Total tardiness; "order fulfillment performance"; effect of workforce flexibility on performance
(Han et al., 2024) Strategic workforce planning for production of prefabricated bathroom units: an advanced markovian approach	Offsite construction / manufacturing – prefabricated bathroom units (PBUs) production (case context in Singapore)	ANA/QUE + META: Markovian modelling with queueing-theory relationships (e.g., Little's law) in a hierarchical planning approach; solved via metaheuristic optimisation and evaluated through scenario/sensitivity analysis	U3	Long-run stochastic effects + explicitly modelled uncertain human-caused events	H3	Individual-level behavioural tendencies affecting task assignment (hierarchical individual → operations structure).	Cycle time; workforce cost; time saved via cross-training (e.g., hours saved); productivity/flexibility.
(A. Nembhard, 2014) Cross training efficiency and flexibility with process change	Manufacturing (operating system subject to process changes; not industry-specific in the abstract)	SIM (DES): discrete-event simulation to study cross-training efficiency/flexibility under process change, including operational conditions such as learning/forgetting–type dynamics and workforce variability parameters	U2	Absenteeism/turnover + process change (frequency/magnitude) as perturbation sources (scenario-based in simulation)	H2	Learning & forgetting; related human effects (motivation/fatigue /vigilance mentioned as relevant)	Productivity/losses from training disruptions; system performance (net gains under different cross-training levels)
(Hopp et al., 2009) Design and control of agile automated CONWIP production lines	Manufacturing – CONWIP production line with agile automated features	ANA (MDP) + SIM: analytical modelling using a Markov decision process to characterise/control policies, complemented with simulation experiments for performance evaluation	U1	Robustness/variation discussed (CONWIP "more robust" than push), without explicit uncertainty modelling in the accessible excerpt	H0	Cross-training as a single flexible server; no explicit human behaviour	System efficiency and robustness (specific metrics not listed in the accessible excerpt)
(Kim & Nembhard, 2013) Rule mining for scheduling cross training with a heterogeneous workforce	General operations setting – scheduling in a parallel production system with heterogeneous workforce	DM/ML + OPT: proposes an association rule mining–based framework to extract decision rules for scheduling/cross-training; links mined rules to schedule attributes produced	U1	Not visible in the accessible source (likely scenario/data-driven variation)	H1	Skill heterogeneity as input to decision rules (no accessible evidence of behavioural modelling)	Scheduling performance metrics derived from rules (not specified in the accessible source)

		under heterogeneous workforce assumptions					
(Ayough et al., 2025) Modeling workers rotation in divisional seru production systems	Manufacturing – divisional seru production systems (DSPS)	OPT (MINLP) + META: develops a mixed-integer non-linear optimisation model; solved with exact/solver-based approaches for smaller instances and a metaheuristic (invasive weed optimisation) for larger instances	U0	No uncertainty stated in the accessible snippet	H1	Job rotation (rotation/competency management) as an assignment constraint/decision	Resilience proxy linked to system performance under rotation (objective/metrics not visible in the accessible snippet)
(Iravani et al., 2005) Structural flexibility: A new perspective on the design of manufacturing and service operations	Generic – applicable to manufacturing and service operations	ANA + SIM: defines/quantifies structural flexibility using an index derived from a maximum-flow (network) formulation, illustrated/evaluated via simulation of serial and parallel queueing-network structures	U2	Variability in system dynamics/flows (performance compared under variability; indices validated against performance under stochastic conditions)	H0	Skills/capacity treated structurally (no behavioural/physiological factors)	Performance under variability (e.g., waiting/flow-time type outcomes and comparative performance ranking across designs)
(Doan et al., 2022) Impact of flexible work contracts and multi-skilled agents on a multi-objective workforce planning problem	Services – Brazilian subcontracting company (cleaning, concierge, surveillance services; clients include banks/hospitals/shopping centres)	OPT (multi-objective MILP): mixed-integer linear programming with multiple objectives (e.g., travel cost, workload balance/satisfaction, preference satisfaction); numerical experiments with real company data	U0	No explicit probabilistic/robust uncertainty in the accessible abstract (planning framed as multi-objective)	H2	Preferences/satisfaction (workload balance + worker preferences) explicitly modelled as objectives alongside cost-related objectives	Multi-objective outcomes: travel/assignment cost + satisfaction-related objectives (preference fulfilment / workload balance)
(Valeva et al., 2017) Balancing flexibility and inventory in workforce planning with learning	Generic workforce planning (not restricted to one sector in the abstract)	OPT (stochastic programming): optimisation model balancing capacity flexibility vs. inventory, explicitly incorporating learning effects in workforce planning decisions; evaluated through computational experiments	U3	Stochastic demand explicitly considered (inventory + workforce flexibility as buffers)	H1	Learning-by-doing (human capital accumulation affecting productivity)	Objective/outputs centred on economic performance under demand uncertainty (e.g., expected profit/cost trade-offs) plus inventory/flexibility levels
(Wu et al., 2018) Cross-trained worker assignment problem in cellular manufacturing system using swarm intelligence metaheuristics	Manufacturing – cellular manufacturing system	OPT + META: formulates a cross-trained worker assignment model and solves it using swarm-intelligence metaheuristics; reports computational performance/solution quality comparisons	U0	Deterministic assignment/optimisation framing (no uncertainty highlighted in the accessible PDF view)	H0	Skill/cross-training as a structural capability only	Assignment-quality / efficiency objective(s) from the optimisation comparison (reported objective value(s) for worker assignment; performance of metaheuristics)

(Fernandes et al., 2022) Worker assignment in dual resource constrained systems subject to machine failures: a simulation study	Manufacturing – dual resource constrained (DRC) system with machine failures	SIM: simulation-based evaluation of worker assignment policies under machine-failure disruptions in DRC settings	U2	Random machine failures/breakdowns in the simulated DRC environment	H0	Workforce treated as assignable capacity/skills (no behavioural factors)	Delivery/flow robustness measures under failures (e.g., % tardy jobs / tardiness-related indicators and throughput/throughput-time-type outcomes)
(De Sanctis et al., 2018) Resilience for lean organisational network	Manufacturing (lean organisational network; case-based application in a manufacturing company)	SIM + NET/CASE: proposes a modelling methodology (Lean Structural Network) to assess resilience and evaluate interventions such as cross-training and staff relocation; includes a simulation model and a manufacturing case study.	U1	"Unexpected shortages"/disturbances analysed as disruptions (scenario-style impacts on KPIs)	H2	Learning curve + "attitude" differences of process owners explicitly discussed	Network/service resilience expressed via local/global KPI impact under shortages and a resilience-oriented quantification approach (impact propagation/shortage effect on KPIs)
(Henao et al., 2022) Multiskilled personnel assignment problem under uncertain demand: A benchmarking analysis	Retail (motivated by / tested with a Chilean retail store context)	OPT (stochastic programming) + benchmarking: formulates a multiskilled personnel assignment problem under demand uncertainty and benchmarks solution approaches through computational experiments (including case-motivated settings).	U3	Uncertain demand; compared two-stage stochastic optimisation, robust optimisation, and deterministic/myopic approaches	H0	Skill-chaining (2-chaining) as structural flexibility (no behavioural factors)	Average total cost (incl. surplus/shortage cost logic) and performance across demand-variability levels (in/out-of-sample benchmarking)
(Henao et al., 2023) Multiskilled personnel assignment with k-chaining considering the learning-forgetting phenomena	Retail (personnel assignment with multiskilling/skill chains, evaluated under realistic learning dynamics)	OPT (MIP/MINLP with learning–forgetting): models multiskilled assignment using k-chaining while explicitly incorporating learning/forgetting effects; assessed via computational experiments.	U3	"Uncertain workforce demand" explicitly referenced; k-chaining framed to match uncertainty	H1	Learning/forgetting (heterogeneous workforce productivity evolution)	Cost/reliability style outputs for personnel assignment under uncertainty (evaluation of multiskilling benefits with learning/forgetting)
(Barkokebas et al., 2023) Assessment of digital twins to reassign multiskilled workers in offsite construction based on lean thinking	Offsite construction (OSC production/operations; lean-oriented performance assessment)	SIM (digital-twin / surrogate simulation) + scenario analysis: uses a simulation-based "digital twin" (as a surrogate) to test policies for reallocating multiskilled workers and evaluates impacts through scenario experimentation and lean-performance lenses.	U1	Uncertainty described as production uncertainty / multiple projects / variable market demands; DT enables adaptive reassignment (uncertainty is motivation; formal stochastic detail not visible in accessible sources)	H0	Multiskilling as structural flexibility (human decision-making/fatigue not described in accessible abstract)	Production-performance improvement via reassignment (lean-performance style outcomes; exact metrics not listed in accessible abstract/TL; framed as improving flexibility and production outcomes)

(Henao et al., 2016) Multiskilling with closed chains in a service industry: A robust optimization approach	Service industry (multiskilled workforce design under uncertainty; closed-chain skill structures)	OPT (robust optimization): develops a robust-optimization model for multiskilling design using closed chains under demand uncertainty, and evaluates robustness via computational experiments.	U3	Demand uncertainty handled via robust optimisation (conservatism/robustness parameterisation)	H0	Skill structure (closed chains) as structural flexibility	Weekly total cost (explicit surplus/shortage cost structure) and robustness–cost trade-offs across demand variability / conservatism settings
(Heyhat et al., 2026) Data-driven distributionally robust optimization for resilient healthcare resource planning and crisis mitigation	Healthcare (resource/workforce planning for crisis mitigation; resilience-oriented)	OPT (data-driven DRO): proposes a distributionally robust optimization model (data-driven) for resilient healthcare resource planning under uncertainty, aimed at crisis mitigation; validated through numerical/case-based experiments.	U3	Distributionally robust optimisation (data-driven ambiguity about probability distributions) for crisis planning	H0	Focus is on resource planning robustness; human behavioural factors not evident in accessible citation/summary	Resilience framed as robustness of healthcare resource plans for crisis mitigation (shortage/coverage and cost-type performance under worst-case/ambiguous demand; exact metrics not listed in accessible citation snippet)
(Ferjani et al., 2017) A simulation-optimization based heuristic for the online assignment of multi-skilled workers subjected to fatigue in manufacturing systems	Manufacturing systems (online assignment of multi-skilled workers with fatigue)	SIM-OPT (simulation + heuristic): develops an online assignment heuristic for multi-skilled workers with fatigue, supported and tuned/evaluated through simulation(-optimization) experiments.	U2	Online/real-time assignment context typically entails stochastic system evolution (paper explicitly couples simulation + optimisation; uncertainty formalisation not visible in the listing)	H2	Fatigue explicitly modelled (human performance degradation)	Joint operational + human-sustainability proxies: production performance (assignment effectiveness) and fatigue-related measures (fatigue impact tracked as part of the decision/assessment)
(Zelenyanszki et al., 2022) Extending the scope of practice for experienced assistant practitioners in breast screening and the impact on service resilience	Healthcare (NHS breast screening service; radiography workforce)	EMP (service evaluation; mixed evidence): evaluates a local trial deploying pairs of assistant practitioners; uses performance/audit indicators (repeat/recall rates) plus prospective notes and content analysis of staff feedback.	U1	Resilience discussed in service-delivery terms (coping capacity/continuity), not as a formal stochastic model (based on available summaries)	H2	Role expansion, autonomy/voice, staff engagement/retention mechanisms	Service-resilience proxy is largely organisational/service continuity: improvements linked to workforce resilience, job satisfaction/engagement/retention (quantitative service metrics not visible in the accessible summary) (ScienceDirect)

(Tian et al., 2024) Balancing heterogeneous assembly line with multi-skilled human-robot collaboration via Adaptive cooperative co-evolutionary algorithm	Manufacturing (heterogeneous assembly line; human–robot collaboration)	OPT-META (metaheuristic): proposes an adaptive cooperative co-evolutionary algorithm for assembly-line balancing with multi-skilled human–robot collaboration; assessed via computational experiments/benchmarks.	U0	No uncertainty highlighted in the accessible abstract snippets (modelled as an optimisation problem)	H1	Workforce heterogeneity / semi-skilled workers + cobot collaboration (capability differences)	Multi-objective productivity/cost performance: explicitly framed as maximising productivity and minimising cost (line-balancing/task-allocation performance)
(Sarihi et al., 2020) Multiskilled project management workforce assignment across multiple projects regarding competency	Project management / multi-project environment (competency-based workforce assignment across projects)	OPT + SIM/FRAME: proposes a competency-aware approach for workforce assignment across multiple projects (model-based, supported by a simulation framework/experimental evaluation as described in the paper).	U0	No explicit uncertainty visible in accessible listing snippets (assignment across multiple projects)	H1	Competency/skill matching (human capital as competency, not behaviour)	Competency-based assignment quality + utilisation/capacity allocation style outputs (exact metric list not visible in accessible abstract snippet)
(Li et al., 2025) A multitasking workforce-constrained flexible job shop scheduling problem: An application from a real-world workshop	Manufacturing – real-world workshop (flexible job shop scheduling)	OPT (MILP) + HEUR: proposes a MILP formulation and an improved genetic algorithm (IGA4MW) for the multi-objective scheduling problem; computational experiments plus real-case validation in a workshop setting	U0	No explicit uncertainty modelling indicated (standard deterministic scheduling formulation)	H1	Multi-skilled / multitasking workforce constraints (skills as assignment feasibility/capacity)	Makespan; total weighted tardiness (objective/primary performance outputs)
(Szwarc et al., 2024) Robust scheduling of multi-skilled workforce allocation: job rotation approach	Software development organisations (workforce allocation / job rotation)	OPT (CP/CSP): formulates robust scheduling/allocation as a constraint satisfaction problem (CSP) with a declarative reference model; computational/illustrative scenarios to evaluate robustness under disruptions	U2	Explicit “unexpected events” considered (e.g., absenteeism, project priority shifts) within a robust scheduling framing	H2	Learning & forgetting dynamics tied to assignments / job rotation (competency evolution)	Schedule robustness/feasibility under events; project/work execution outcomes (time/quality of schedule in presence of disruptions)
(Abreu et al., 2023) Multiskilled labor force: a discussion of this missing link of lean construction in Brazilian companies	Construction – lean construction context (Brazilian companies)	CONC/DISC: discussion paper analysing benefits and barriers of multiskilled labour in lean construction; conceptual synthesis rather than a formal empirical or optimisation study	U1	Uncertainty/variability discussed as inherent to construction (conceptual/empirical discussion, not formal stochastic/robust modelling)	H2	Human/organizational adoption of multiskilling (training, implementation barriers/enablers in firms)	Lean/operational improvement proxies reported at discussion level (e.g., reduced variability/waste, improved productivity/flow/reliability) rather than a single formal metric

(Y. Li et al., 2007) An integrated staff-sizing approach considering feasibility of scheduling decision	Services / healthcare staffing context (example focuses on nurse sizing and scheduling feasibility)	OPT (MOLP) + PROC: integrated approach combining staff sizing and feasibility of scheduling; multi-objective linear programming with an iterative procedure to ensure feasible schedules	U0	No explicit uncertainty component evident from accessible abstract text (staff-sizing integrated with schedule feasibility)	H0	Workforce treated as staffing/scheduling resources (no explicit behavioural/learning/wellbeing constructs visible in abstract)	Schedule feasibility + staffing/sizing performance (e.g., meeting staffing requirements with feasible schedules; cost/levels implied but not specified in abstract)
(Yoo et al., 2024) Illustrating the Anticipate, Recruit, Retain, Adapt, Sustain (ARRAS) framework for surge capacity. how Bangladesh, Sri Lanka, and Nepal maintained their health workforce during COVID-19	Healthcare – national health workforce surge capacity (Bangladesh, Nepal, Sri Lanka; COVID-19)	EMP-MIX: mixed-methods study integrating key-informant interviews with descriptive quantitative trend analysis of national workforce counts (2018–2021) to develop/illustrate the ARRAS framework	U1	Crisis-driven surge context (unexpected demand shock) addressed via mixed-methods framework; not a formal stochastic optimisation model	H3	Strong HRH focus: recruit/retain/adapt/sustain strategies; incentives, re-skilling, telemedicine; coordination issues	National workforce maintenance proxies: per-capita workforce; trends in doctors/nurses pre/post; (limited ability to rapidly expand during crisis)
(Givi et al., 2015) Production planning in DRC systems considering worker performance	Manufacturing – dual resource constrained (DRC) production systems	ANA/COMP: model-based study incorporating worker performance in DRC production planning; evaluates policies via computational experiments (comparative scenarios / performance outcomes)	U1	"Worker performance" variation across production run/configurations discussed; treated as performance-response rather than external probabilistic demand uncertainty (based on available summary)	H2	Human performance affects system outcomes (productivity + quality)	Time-related cost + quality-related cost (twofold cost perspective / overall system performance vs flexibility level/transfer policy/configuration)
(Attia et al., 2014) Considering skills evolutions in multi-skilled workforce allocation with flexible working hours	Manufacturing companies – multi-period project/workforce allocation context	OPT (model + GA): mathematical model for multi-skilled workforce allocation with flexible working hours and skill evolution; solved using a genetic algorithm and assessed through experimental instances (e.g., ~400 projects)	U1	Market volatility is the motivation; model uses endogenous task durations via experience/competence evolution (not classical stochastic demand).	H2	Skills/experience evolution (learning over time) + flexible working hours.	Reported criteria include: project penalty; overtime ratio; increase in working hours due to multi-skilling; loss of future temporal flexibility; evolution of workforce experience.
(Coates et al., 2021) Health workforce strategies in response to major health events: a rapid scoping review with lessons learned for the	Healthcare – health workforce strategies across major health events (incl. COVID-19)	REV (rapid scoping review): rapid scoping review (protocolled screening/extraction) synthesising strategies used to mobilise/expand health workforce capacity across major events, with lessons for COVID-19	U1	Reviews major events where shocks combine: increased demand + reduced workforce availability + infrastructure impacts (conceptual synthesis, not a single formal uncertainty model)	H3	Workforce capacity levers: increasing numbers, increasing flexibility/scope-of-practice, supporting/sustaini	Heterogeneous evaluation metrics across included studies; key finding: most papers lack substantive evaluation (so metrics often weak/variable)

response to the COVID-19 pandemic						ng workers; also barriers/facilitators	
(Kelsey, 2006) Use 'em or lose 'em – The licensed practical nurse	Healthcare – nursing workforce / role utilisation (licensed practical nurse)	EMP-CASE (DESCR): descriptive practice/role redesign report (how LPN work was restructured, training/tools used, and implementation narrative); not a formal optimisation/simulation study	U1	Change motivated by operational/role constraints (not formal uncertainty modelling)	H3	Role redesign with training/orientation tools; staff acceptance barriers; job satisfaction & teamwork explicitly discussed	Job satisfaction; unit flexibility; teamwork (reported positive impact)
(Fægri et al., 2010) Introducing knowledge redundancy practice in software development: Experiences with job rotation in support work	Software development – support work / job rotation	EMP-ACTION: action research / experience-based study of job rotation to build knowledge redundancy (qualitative data such as interviews/observations and intervention learning cycles)	U1	Risk/continuity motivation via "knowledge redundancy"; not a stochastic optimisation framing in accessible summary	H3	Work design + psychosocial measures: job burnout, role conflict, role ambiguity; perceived benefits/limitations of rotation	Knowledge redundancy / work-design construct outcomes; burnout/role conflict/role ambiguity indicators used/analyzed
(Henao et al., 2019) Multiskilled workforce management by utilizing closed chains under uncertain demand: A retail industry case	Retail services / service sector (multi-department retail setting; case-based context)	ANA + HEU + SIM + OPT (LP): three-stage methodology combining (i) an analytic expression to estimate multiskilled staffing needs by department, (ii) constructive heuristics to generate closed-chain skill structures, and (iii) Monte Carlo simulation + linear programming to evaluate chains under stochastic demand.	U3	Uncertain demand explicitly central; approach targets robustness under demand variability in retail workforce management.	H1	Multi-skill structure via closed chains / cross-training design (skills as coverage capacity).	Robustness/performance under demand uncertainty (e.g., demand coverage/service level vs staffing cost trade-offs; shortage/over-coverage consequences).
(Mac-Vicar et al., 2017) Real-time recovering strategies on personnel scheduling in the retail industry	Retail services (schedule adjustments under demand variation and absenteeism; tested with real retailer data)	OPT + HEU (real-time recovery algorithms): mathematical problem specification + algorithms to search the best adjustments across contingency resources (including transfers of multiskilled employees); solution is simplified via two greedy heuristics; validated with real data from a Chilean retail chain.	U2	Explicit short-term disruptions: unexpected demand variations and unscheduled employee absences	H2	Recovery actions account for worker dissatisfaction from schedule modifications (human acceptance/cost of change)	Profit impact (lost profit); recovery effectiveness; worker dissatisfaction proxy tied to schedule changes

(Spanier et al., 2021) Principles and practice of deploying a flexible physician workforce for COVID-19 care wards from a Dutch hospital	Healthcare – hospital (Dutch teaching hospital; physician flex pool for COVID-19 cohort wards)	EMP-CASE (DESCR) / PRACTICE (opinion-style implementation report): practice-focused description of how a flexible physician workforce was organised and managed (principles, coordination, training/upskilling needs). No formal optimisation/simulation model.	U1	Pandemic surge capacity problem statement (shock context); principles-based guidance rather than formal uncertainty model	H2	Re-/upskilling; redeployment; "solidarity, flexibility and transparency" as enablers	Surge capacity / ability to sustain COVID + regular care (qualitative operational continuity proxy)
(Xu et al., 2021) A vital layer of support: one safety net hospital's palliative care response to the pandemic	Healthcare – hospital (palliative care service) (public safety-net hospital during COVID-19 surge)	EMP-CASE (DESCR): descriptive case report of service redesign and redeployment (including targeted training of volunteers / internally redeployed providers), supported by operational counts and service activity figures (descriptive, not model-based).	U1	Surge shock context (rapid increase in critically ill patients); adaptive staffing response	H2	Rapid team reconfiguration + targeted training of volunteers/redeployed providers	Output/coverage proxies: #patients served (276); #volunteers (12); #patients seen by volunteers (111); ability to meet consult demand
(Ebm et al., 2025) Return on investment of rapid ICU workforce upskilling: an economic and cost-effectiveness analysis	Healthcare – intensive care (ICU) (large-scale ICU upskilling initiative; crisis capacity)	ECON-EVAL (deterministic model + PSA): societal economic evaluation and ROI estimation using deterministic modelling, with probabilistic sensitivity analysis across plausible scenarios (throughput, training efficacy, system parameters).	U3	Explicit scenario uncertainty handled via probabilistic sensitivity analysis across plausible parameter variations	H2	Large-scale workforce upskilling; competency-based training effectiveness proxy (QAHW)	ROI (%); break-even time (days); total investment; cost per participant; cost per QAHW; capacity expansion proxy
(Tsang et al., 2021) Blockchain-IoT-driven nursing workforce planning for effective long-term care management in nursing homes	Healthcare – long-term care / nursing homes (case study: Hong Kong nursing home)	OPT (integer programming-style staffing model) + META (GA) + SYS/CASE: proposes a blockchain–IoT-enabled system to monitor care services and feed data into a nursing staffing optimisation problem (binary/integer decision variables for staffing/assignment/overtime and temp hours; hard/soft constraints). Solved with a genetic algorithm (with constructive heuristic initialisation) and demonstrated via a real case study, reporting	U1	Time-varying / fluctuating care demand described, with real-time data acquisition; optimisation presented without explicit robust/stochastic uncertainty set in the sections accessed.	H2	Staff-task flexibility; heterogeneous workforce; explicit "skills" (managerial/professional); workload balancing.	Max quality of care (QoC) at lowest cost; workload balance; staffing level/solution quality in case study.

		cost and service-fulfilment outcomes.					
(White et al., 2026) Voices from the bench: focus group insights on shared research resource sustainability amid federal policy shifts	Shared Research Resources (SRRs) / research core facilities (biomedical research support)	EMP-MIX: hybrid focus groups + quasi-survey, qualitative thematic analysis complemented with descriptive quantification (awareness/concern patterns)	U1	Policy/funding uncertainty and disruption from federal policy shifts discussed qualitatively (no formal stochastic modelling)	H1	Workforce resilience mechanisms (e.g., cross-training, strategic recruitment, leadership alignment, operational coordination practices) discussed qualitatively	No operational KPI; qualitative resilience/sustainability themes + awareness/concern indicators (perceptions, reported priorities)
(Lian et al., 2025) Valuing labor flexibility in cross-training using a real options approach	Manufacturing (generic new-product setting with a single bottleneck resource)	ANA: stochastic dynamic programming / real options valuation with trinomial lattice approximation of demand uncertainty; staged cross-training decisions (redundancy at the bottleneck)	U3	Stochastic demand uncertainty explicitly modelled (continuous-time process approximated via trinomial lattice); penalty structure for unmet demand	H0	Cross-training modelled as structural flexibility (multiskilling level / redundancy investment), without learning/behavioural dynamics	Expected NPV / flexibility (option) value of cross-training investment; economic value of redundancy and cost impact of unmet demand
(Slomp et al., 2005) Cross-training in a cellular manufacturing environment	Manufacturing – cellular manufacturing	OPT: integer programming (two-stage approach) to design cross-training under multiple "situations" (demand mix + labour supply)	U1	Scenario-based variability: multiple demand situations + labour supply situations (e.g., worker absence) treated deterministically (no probabilistic/stochastic model)	H1	Worker heterogeneity in efficiencies (assumed end-of-learning-curve), cross-training feasibility constraints; workload-balance + "social justice" motivation	Operating cost proxy via bottleneck workload, training costs; implied robustness via workload balancing under different demand/absence situations
(Nembhard et al., 2005) A real options model for workforce cross-training	Manufacturing/operations (generic production setting)	ANA + SIM: real-options valuation (binomial lattice / American option framing) + simulation experiments to evaluate cross-training investment timing/value	U3	Multiple uncertainties: stochastic value of output (e.g., diffusion process), + random events (e.g., absenteeism, product/skill requirement changes) incorporated in the valuation framework	H2	Dynamic skill acquisition (learning) explicitly represented (workers improve skill levels; no skill loss assumed), plus	Real option value / NPV under flexibility (e.g., option value of cross-training, NPV comparison between strategies) as resilience-through-flexibility valuation

						workforce flexibility investment/coverage decisions	
(Bokhorst et al., 2004) On the who-rule in dual resource constrained manufacturing systems	Manufacturing – Dual Resource Constrained (DRC) systems	SIM: discrete-event simulation comparing alternative who-rules (worker assignment/dispatching rules) under different flexibility configurations	U2	Stochastic shop-floor variability represented within simulation dynamics (system congestion/flow variability under DRC conditions)	H1	Structural human factors via worker assignment rules + cross-training/flexibility configuration (no learning dynamics)	Mean flow time and flow-time variability (std. dev.) as performance/robustness proxies
(Sanders & Ritzman, 2004) Using warehouse workforce flexibility to offset forecast errors	Warehousing / distribution operations (public warehouse case context)	SIM: Monte Carlo simulation of daily labour scheduling with factorial variation of forecast error (bias + std. dev.) and flexibility levers (cross-training proxy + PT mix)	U2	Explicit forecast-error uncertainty: demand requirement sampled from distributions; forecast bias and standard deviation controlled experimentally	H0	Flexibility captured as structural interchangeability (number of work groups as cross-training surrogate) + FT/PT mix; learning/efficiency losses only discussed as limitation	Total cost (TC) (labour + inventory carryover/penalty for delayed work) and cost sensitivity to forecast bias/std. dev. (buffering effect of flexibility)
(Hoyt & Matuszek, 2001) Testing the contribution of multi-skilled employees to the financial performance of high-tech organizations	High-tech manufacturing organizations (e.g., automotive suppliers, electronic instrumentation, semiconductor manufacturing)	EMP-CASE(QUAN): cross-sectional survey (work environment supporting multi-skilled workforce) + archival financial data; factor analysis + Data Envelopment Analysis (DEA) to classify “successful” vs “non-successful” firms; logistic regression testing MSW contribution	U1	Environmental turbulence / “hostile–dynamic” context discussed as backdrop, but not modelled probabilistically	H1	Multi-skilled workforce as organisational capability (skill diversity/adaptability/mobility, cross-training orientation) captured via survey constructs	Financial performance ratios (e.g., operating margin, gross margin, sales-to-inventory, ROA) + relative efficiency / success classification via DEA
(Jensen, 2000) The impact of resource flexibility and staffing decisions on cellular and departmental shop performance	Manufacturing shop configurations (cellular vs departmental layouts; multi-family flow shop)	SIM (discrete-event simulation): factorial experiment varying layout (department/hybrid/strict cell), staffing levels, workload balance, and labor transfer rules (LQ/EDD/CYC); ANOVA + Tukey comparisons	U1*	Workload balance/imbalance scenarios and due-date tightness (TWK-based rule); stochasticity inherent to simulation but distributions not fully specified in extractable detail	H0	Labor flexibility treated as reassignment/transfer rules (cross-trained availability), without behavioural/learning dynamics	Mean flow time (WIP proxy), mean tardiness, root mean square tardiness (TRMS)

(Park & Bobrowski, 1989) Job release and labor flexibility in a dual resource constrained job shop	Manufacturing – dual resource constrained (DRC) job shop (hypothetical/simulated environment)	SIM (discrete-event simulation): compares release mechanisms (FFL vs BIL), labor assignment (centralized vs decentralized), and multiple labor flexibility structures; batch means data collection	U2	Stochastic due-date tightness explicitly represented via triangular distributions; shop dynamics evaluated through simulation outcomes	H0	Cross-training / labor-flexibility structures and transfer costs modelled as structural parameters (no learning/behavioural effects)	Total cost per day (inventory holding + late penalty + worker transfer costs) + average lateness, proportion tardy, waiting time, time in backlog file, worker immobility
(Rochette & Sadowski, 1976) A statistical comparison of the performance of simple dispatching rules for a particular set of job shops	Manufacturing – dual resource constrained job shop (two departments; multiple dispatching rules)	SIM + statistical testing: simulation of dispatching rules across shop-load levels; ANOVA and hypothesis tests to compare rules and resource configurations	U2	Explicit stochastic assumptions: Poisson job arrivals and exponentially distributed operation times (shop-load driven variability)	H0	Workforce flexibility represented as a switching permission + relative-efficiency loss parameter (structural flexibility only)	Mean flow time and mean job tardiness (primary performance criteria)
(Graham & Rosenthal, 1986) Flexible manufacturing systems require flexible people	Manufacturing – Flexible Manufacturing Systems (FMS) implementation (multiple industrial settings; fieldwork-based insights)	CONC/FRAME (fieldwork-based): observational/fieldwork study across several FMS organisations, synthesising human/organisational requirements for achieving technical flexibility	U1	Implementation ambiguity and operational uncertainty discussed conceptually (no formal uncertainty modelling)	H1	Emphasis on cross-training, job rotation, cross-functional cooperation/teamworking as enabling mechanisms for flexibility	Qualitative implementation/performance outcomes (effective attainment of FMS flexibility; avoiding bottlenecks/underutilisation through “flexible people”)

Codes:

- SIM: simulation (e.g., discrete-event simulation).
- ANA: analytical modelling (e.g., Markov/MDP, queues) and/or formulation with analytical logic.
- OPT: optimisation (e.g., MIP/goal programming) + algorithm/procedure.
- EMP-CASE(QUAN): case study with quantitative analysis (survey/KPIs).
- EMP-MIX: mixed (cases + survey or other combinations).
- EMP-LONG: empirical longitudinal (temporal follow-up).
- CONC/FRAME: conceptual framework (with or without illustrative cases)

Appendix 3. Complete evidence synthesis matrix RQ2

Article	Stage	Explicit enablers (E+)	Explicit barriers (E–)	Evidence anchor	Resilience framing
(Felan et al., 1993) Labour flexibility and staffing levels in a dual-resource constrained job shop	O	SKILLS (cross-training vs increasing staffing)	—	Experimental design + metrics: flow time/WIP, tardiness, % tardy, utilisation	R-proxy
(Slomp & Molleman, 2002) Cross-training policies and team performance	O	SKILLS (cross-training policies under absenteeism and order-mix)	COORD (coordination effort measured explicitly)	Explicit metrics: coordination effort, bottleneck-worker load; shocks: absenteeism + demand/mix	R-proxy
(Sawhney, 2013) Implementing labor flexibility: A missing link between acquired labor flexibility and plant performance	I–O	TEAM/ORG (implementation / "implementation sophistication" mechanism), SKILLS (acquired vs implemented)	TEAM/ORG (implementation side effects/frictions as part of the mechanism)	Empirical links: acquired→implemented→performance; proxies: WIP and manufacturing cost	R-proxy
(Felan & Fry, 2001) Multi-level heterogeneous worker flexibility in a DRC job-shop	O (and some I)	SKILLS (multi-level flexibility), HUM-DYN (proficiency heterogeneity)	COST/FEAS (training cost proxy / labour variance)	Explicit factors: heterogeneity and levels; metrics: tardiness/% tardy, inventory, labour variance (proxy)	R-proxy
(Hopp & Oyen, 2004) Agile workforce evaluation: a framework for cross-training and coordination	I–O	SKILLS, COORD (coordination as an explicit mechanism in the framework)	—	Framework: cross-training + coordination; proxies discussed: mean/variance of cycle time, delivery reliability, quality impacts	R-proxy
(Grant & Hallam, 2016) Team performance in a lean manufacturing operation: it takes the will and a way to succeed	I–O	TEAM/ORG (team collaboration, shared priorities), SKILLS (multifunctional teams)	—	Longitudinal empirical; metrics: schedule performance, quality, labour efficiency	R-none
(Fraser & Hvolby, 2010) Effective teamworking: can functional flexibility act as an enhancing factor?	I–O	SKILLS (job rotation/functional flexibility), TEAM/ORG (team processes measured)	—	Case+quant: team processes (communication, conflict resolution, etc.) + team performance constructs	R-none
(Hopp et al., 2004) Benefits of skill chaining in serial production lines with cross-trained workers	O	SKILLS (skill chaining explicitly)	—	Proxies: throughput, WIP/inventory, cycle time; stochastic modelling	R-proxy
(McCreery & Krajewski, 1999) Improving performance using workforce flexibility in an assembly environment with learning and forgetting effects	I–O	SKILLS, HUM-DYN (learning/forgetting explicitly modelled)	HUM-DYN (forgetting as explicit performance degradation)	Simulation with learning/forgetting; metrics: throughput, WIP, utilisation, efficiency	R-proxy

(Slomp & Suresh, 2005) The shift team formation problem in multi-shift manufacturing operations	I	SKILLS (skills constraints in shift-team formation)	COST/FEAS (explicit cost/flexibility trade-off in goal programming)	OPT: multi-objective goal programming balancing flexibility and labour-related costs	R-none
(Jordan et al., 2004) Chained cross-training of workers for robust performance	O	SKILLS (chaining as explicit design)	—	Queueing/ANL: time-in-system/response time and utilisation; "robust performance" framing	R-explicit
(Julie Yazici, 2005) Influence of flexibilities on manufacturing cells for faster delivery using simulation	O	SKILLS (labour flexibility as redeployable capacity)	—	SIM: "volatile demand" + metrics lead time/delivery speed, utilisation	R-proxy
(Azizi & Liang, 2013) An integrated approach to worker assignment, workforce flexibility acquisition, and task rotation	I–O	SKILLS (flexibility acquisition + assignment), TEAM/ORG (task rotation as an explicit organisational decision)	COST/FEAS (training + productivity-loss explicitly costed)	OPT+HEU: objective = total cost (training + flexibility + productivity-loss); includes training/rotation plan	R-proxy
(McCreery et al., 2004) Performance implications of assembly work teams	O	TEAM/ORG (team configuration/task sharing), HUM-DYN (learning/forgetting explicitly discussed/modelled)	—	SIM: learning/forgetting + sensitivity to variety/complexity; metrics throughput and productivity/efficiency	R-proxy
(Kim & Nembhard, 2010) Cross-trained staffing levels with heterogeneous learning/forgetting	I–O	SKILLS (cross-trained staffing), HUM-DYN (heterogeneous learning/forgetting explicitly)	HUM-DYN (heterogeneity/forgetting affects staffing required)	Explicit outcome: minimum staffing level to meet production requirement; SIM experimentation	R-proxy
(Park, 1991) The examination of worker cross-training in a dual resource constrained job shop	O	SKILLS (cross-training matrix varied in DES)	—	SIM in DRC job shop; performance metrics: flow time / WIP / tardiness-type indicators	R-proxy
(Henao et al., 2015) The impact of multi-skilling on personnel scheduling in the service sector: a retail industry case	O	SKILLS (multi-skilling represented as parameters/heterogeneity)	—	OPT (MILP) for scheduling; outputs: total cost + understaffing/coverage proxy; model stated as deterministic (excludes demand uncertainty/unplanned absences)	R-proxy
(Van Oyen et al., 2001) Performance opportunity for workforce agility in collaborative and noncollaborative work systems	O	TEAM/ORG (collaborative vs noncollaborative work structure explicitly modelled)	—	ANL (queueing/stochastic) comparing work-system structures; metrics: WIP / cycle time / throughput	R-proxy
(Porto et al., 2022) Solving a staffing problem with annualized hours, multiskilling with 2-chaining, and overtime: A retail industry case	I–O	SKILLS (2-chaining multiskilling plan), COST/FEAS (annualized hours + overtime as explicit feasibility mechanisms)	COST/FEAS (cost trade-offs explicitly evaluated: total cost; coverage via overtime; under/overstaffing outcomes)	OPT (MILP) determines workforce size + training plan + weekly allocation of regular/overtime; scenario experiments (demand profiles / demand-variability levels)	R-proxy

(Porto et al., 2025) Improving the robustness of retail workforce management with a labor flexibility strategy and consideration of demand uncertainty	I–O	SKILLS (training plan/2-chaining as structural flexibility)	COST/FEAS (explicit cost components: wages/training/over- & understaffing penalties; robustness vs deterministic benchmark)	OPT (two-stage stochastic); evaluates robustness under demand uncertainty; objective decomposed into labour cost components	R-explicit
(Olivella & Nembhard, 2017) Cross-training policies for team cost and robustness	O	SKILLS (cross-training policy design)	COST/FEAS (cross-training cost + unmet demand used explicitly)	SIM evaluates policies under demand-mix bounds + absenteeism; outputs: cross-training cost + unmet demand (incl. due to absenteeism)	R-explicit
(Tiwari & Roy, 2002) Application of an evolutionary fuzzy system for the estimation of workforce deployment and cross-training in an assembly environment	I	SKILLS (cross-training/deployment estimated via fuzzy rules)	—	COMP/AI (evolutionary fuzzy expert system); outputs: estimation/fitness and recommended cross-training/deployment (no operational resilience proxies reported)	R-none
(Mou & Robb, 2019) Real-time labour allocation in grocery stores: a simulation-based approach	O	COORD (real-time labour allocation policies), SKILLS (skill range/proficiency as operational attributes)	—	SIM (retail store simulator); evaluates reallocation rules; outputs include service/performance under understaffing	R-proxy
(Porto et al., 2019) Hybrid flexibility strategy on personnel scheduling: Retail case study	O	SKILLS (multiskilling as explicit flexibility mechanism)	COST/FEAS (labour cost and coverage trade-offs explicitly evaluated)	OPT (MILP); demand variability handled via deterministic scenarios; outputs: labour cost + coverage/service-quality proxy (under/overstaffing)	R-proxy
(Iravani & Krishnamurthy, 2007) Workforce agility in repair and maintenance environments	O	SKILLS (partially cross-trained repair crews as policy structure)	COST/FEAS (repairman cost explicitly traded off with downtime)	ANA (Markov/queueing); compares policies; outputs: total average machine downtime + repairman cost	R-proxy
(Gnanlet & Gilland, 2014) Impact of productivity on cross-training configurations and optimal staffing decisions in hospitals	I–O	SKILLS (cross-training configurations; staffing decisions), HUM-DYN (productivity effects for cross-trained staff explicitly included)	—	ANA/OPT (queueing + optimisation); uncertain demand; outputs: labour cost and demand coverage/staffing outcomes	R-proxy
(Bokhorst et al., 2004) Development and evaluation of cross-training policies for manufacturing teams	O	SKILLS (cross-training policies developed via goal programming)	—	OPT + SIM; simulation evaluates policies under stochastic system behaviour; outputs: mean flow time + workload distribution variability proxy	R-proxy
(Yang et al., 2007) An evaluation of worker cross training and flexible workdays in job shops	O	SKILLS (cross-training), COST/FEAS (flexible workdays as explicit policy lever)	—	SIM experiments under workload variability; outputs: mean tardiness + mean WIP	R-proxy
(Altendorfer et al., 2021) Service level improvement due to worker cross training with stochastic worker absence	O	SKILLS (skill dedication / cross-training design variable)	—	SIM-OPT (GA) under stochastic worker absence; primary output: service level	R-proxy

(Turan et al., 2021) A multi-skilled workforce optimisation in maintenance logistics networks by multi-thread simulated annealing algorithms	I	SKILLS (multi-skilled workforce in network optimisation)	COST/FEAS (explicit total-cost objective combining workforce/inventory/backorder-type costs)	META optimisation under stochastic failures/repairs; outputs: total cost components under random failures	R-proxy
(Wise et al., 2020) Clarifying workforce flexibility from a division of labor perspective: a mixed methods study of an emergency department team	I–O	TEAM/ORG (work organization & task reassignment), COORD (coordination/work allocation mechanisms)	—	EMP-MIX: time–motion + qualitative follow-up; outputs: role/task overlap and qualitative adaptation evidence	R-proxy
(Suresh & Slomp, 2005) Performance comparison of virtual cellular manufacturing with functional and cellular layouts in DRC settings	O	SKILLS (labour flexibility levels/rules in layout comparison)	—	SIM experiments across layouts with flexibility scenarios; comparative layout performance under scenarios	R-proxy
(Daniels et al., 2004) Flow shop scheduling with partial resource flexibility	O	SKILLS (partial resource flexibility structure in scheduling formulation)	—	ANA/OPT scheduling formulation + heuristics; outputs: profit vs staffing costs / marginal value of flexibility	R-proxy
(Stewart et al., 1994) Mathematical models for developing a flexible workforce	I	SKILLS (who to train/how much as planning decision)	—	OPT models for flexibility development; “fit to planned program” style planning outputs	R-none
(Cuevas et al., 2016) A mixed integer programming approach to multi-skilled workforce scheduling	O	SKILLS (multi-skill coverage structure; balancing coverage ratios)	—	OPT (MIP) deterministic; outputs: coverage of work requirements; balance of coverage ratios	R-none
(Gel et al., 2007) Hierarchical cross-training in work-in-process-constrained systems	O	SKILLS (hierarchical skill sets; floater worker cases)	—	ANA/MDP for CONWIP/WIP-constrained systems; output: throughput under policies	R-proxy
(Easton, 2011) Cross-training performance in flexible labor scheduling environments	I–O	SKILLS (cross-training + staffing/scheduling decisions), COORD (organizational/coordination impact cost included)	COST/FEAS (total labour cost / unmet demand explicitly evaluated; “coordination cost” as an explicit cost component)	Two-stage stochastic + SIM evaluation; outputs: total labour cost and unmet demand	R-proxy
(Chen et al., 2024) Technician routing and scheduling with employees’ learning through implicit cross-training strategy	I–O	HUM-DYN (learning/skill acquisition explicitly modelled), SKILLS (implicit cross-training through assignments)	COST/FEAS (explicit total cost objective: routing + service times)	MDP + ADP; outputs: total cost and learning/cross-training benefits	R-none
(Olivella & Nembhard, 2016) Calibrating cross-training to meet demand mix variation and employee absence	I–O	SKILLS (cross-training set design calibrated to meet feasibility under scenarios)	COST/FEAS (feasibility/robustness requirement under mix + absences as explicit constraint; “calibration” trade-offs)	Scenario-based math programming ensuring feasibility across demand/absence scenarios; output: size/config of cross-training set	R-proxy

(Mou, 2022) Integrated order picking and multi-skilled picker scheduling in omni-channel retail stores	O	SKILLS (multi-skilled pickers in integrated picking+scheduling), HUM-DYN (heterogeneity treated explicitly as parameters)	—	OPT (MIP + decomposition); outputs: total tardiness / order fulfilment performance	R-proxy
(Han et al., 2024) Strategic workforce planning for production of prefabricated bathroom units: An advanced markovian approach	I–O	HUM-DYN (behavioural tendencies / human-caused events explicitly represented), SKILLS (cross-training in strategic planning)	COST/FEAS (workforce cost explicitly output)	Markovian/queueing approach + metaheuristic; outputs: cycle time, workforce cost, time saved via cross-training	R-proxy
(A. Nembhard, 2014) Cross training efficiency and flexibility with process change	I–O	HUM-DYN (learning/forgetting explicitly included), SKILLS (cross-training as design lever)	COST/FEAS (training-disruption losses / net gains under different cross-training levels explicitly evaluated)	SIM under absenteeism/turnover + process change scenarios; outputs: productivity and net-gain style outcomes	R-proxy
(Hopp et al., 2009) Design and control of agile automated CONWIP production lines	O	SKILLS (flexible server/cross-training as capacity structure within CONWIP control)	—	ANA (MDP) + SIM; outputs: efficiency/robustness (metrics not specified in your excerpt)	R-proxy
(Kim & Nembhard, 2013) Rule mining for scheduling cross training with a heterogeneous workforce	O	HUM-DYN (heterogeneous workforce explicitly represented), COORD *(only if rules are explicitly framed as decision rules for scheduling)*	—	DM/ML + OPT: association rules mined for scheduling/cross-training; outputs: scheduling performance metrics derived from rules (not specified in excerpt)	R-none
(Ayough et al., 2025) Modeling workers rotation in divisional seru production systems	I–O	TEAM/ORG (job rotation as explicit management/assignment decision), SKILLS (competency/rotation constraints)	—	OPT (MINLP) + metaheuristic; outputs: system-performance proxy under rotation (metrics not visible in snippet)	R-none
(Iravani et al., 2005) Structural flexibility: A new perspective on the design of manufacturing and service operations	O	SKILLS (structural flexibility index / design of flexibility)	—	ANA + SIM: structural flexibility index validated against performance under stochastic queueing-network variability	R-proxy
(Doan et al., 2022) Impact of flexible work contracts and multi-skilled agents on a multi-objective workforce planning problem	I–O	SKILLS (multi-skilled agents), TEAM/ORG (preferences/satisfaction explicitly included as objectives), COST/FEAS (contract structure as feasibility lever)	COST/FEAS (explicit trade-offs across objectives: cost vs satisfaction/workload balance)	OPT (multi-objective MILP) with objectives incl. preference fulfilment/workload balance + travel/assignment costs	R-none
(Valeva et al., 2017) Balancing flexibility and inventory in workforce planning with learning	I–O	SKILLS (capacity flexibility decisions), HUM-DYN (learning-by-doing explicitly),	COST/FEAS (explicit economic trade-off: inventory vs flexibility; objective in expected profit/cost terms)	OPT (stochastic programming) balancing inventory and workforce flexibility; outputs include economic performance and buffer levels	R-proxy

(Wu et al., 2018) Cross-trained worker assignment problem in cellular manufacturing system using swarm intelligence metaheuristics	O	SKILLS (cross-trained worker assignment model)	—	OPT + META: deterministic assignment optimisation; outputs are objective value/solution quality comparisons	R-none
(Fernandes et al., 2022) Worker assignment in dual resource constrained systems subject to machine failures: A simulation study	O	SKILLS (assignment policies under failures)	—	SIM under random machine failures; outputs: tardiness/throughput-type indicators under breakdowns	R-proxy
(De Sanctis et al., 2018) Resilience for lean organisational network	I–O	SKILLS (cross-training + staff relocation as interventions), HUM-DYN (learning curve + "attitude" differences explicitly discussed)	—	SIM + network/case methodology; disruptions: unexpected shortages; outputs: KPI impact propagation / resilience quantification approach	R-explicit
(Henao et al., 2022) Multiskilled personnel assignment problem under uncertain demand: A benchmarking analysis	I–O	SKILLS (skill-chaining structure in assignment design)	COST/FEAS (explicit cost under uncertainty; benchmarking shows trade-offs across approaches)	OPT under demand uncertainty; compares stochastic/robust/deterministic; output: average total cost across variability levels	R-proxy
(Henao et al., 2023) Multiskilled personnel assignment with k-chaining considering the learning-forgetting phenomena	I–O	SKILLS (k-chaining), HUM-DYN (learning/forgetting explicitly modelled)	COST/FEAS (assignment cost/reliability outputs under uncertainty; trade-offs with learning/forgetting)	OPT (MIP/MINLP with learning–forgetting); outputs: cost/reliability-style performance under uncertain demand	R-proxy
(Barkokebas et al., 2023) Assessment of digital twins to reassign multiskilled workers in offsite construction based on lean thinking	O	COORD (reassignment policies enabled/evaluated via digital twin), SKILLS (multiskilling as flexibility lever)	—	SIM (digital twin) + scenario analysis; outputs: lean-performance improvements from reassignment	R-proxy
(Henao et al., 2016) Multiskilling with closed chains in a service industry: A robust optimization approach	I–O	SKILLS (closed-chain skill design)	COST/FEAS (robustness–cost trade-off explicitly parameterised; weekly total cost with surplus/shortage penalties)	OPT (robust optimisation) under demand uncertainty; outputs: total cost vs conservatism/robustness	R-proxy
(Heyhat et al., 2026) Data-driven distributionally robust optimization for resilient healthcare resource planning and crisis mitigation	I–O	— *(no explicit human/organisational enabler in your snippet beyond "resilient planning" framing)*	COST/FEAS (robustness against distributional ambiguity implies conservatism trade-off in objective/performance)	OPT (data-driven DRO) for crisis mitigation; outputs: robustness of plans under ambiguity (shortage/coverage/cost-type)	R-explicit
(Ferjani et al., 2017) A simulation-optimization based heuristic for the online assignment of multi-skilled workers subjected to fatigue in manufacturing systems	O	SKILLS (online assignment of multi-skilled workers), HUM-DYN (fatigue explicitly modelled)	HUM-DYN (fatigue as explicit performance-degrading constraint/measure)	SIM-OPT heuristic evaluated via simulation; outputs include production performance and fatigue-related measures	R-proxy

(Zelenyanszki et al., 2022) Extending the scope of practice for experienced assistant practitioners in breast screening and the impact on service resilience	I–O	TEAM/ORG (role expansion/scope-of-practice as organisational intervention), SKILLS (expanded competencies via training)	—	EMP service evaluation; outcome framing: service resilience/workforce resilience; uses service indicators + staff feedback	R-explicit
(Tian et al., 2024) Balancing heterogeneous assembly line with multi-skilled human-robot collaboration via Adaptive cooperative co-evolutionary algorithm	O	SKILLS (multi-skilled workforce in line balancing), HUM-DYN (heterogeneity explicitly represented; human–robot capability differences)	COST/FEAS (explicit multi-objective trade-off: maximise productivity, minimise cost)	OPT-META benchmarked; outputs: productivity and cost performance	R-none
(Sarihi et al., 2020) Multiskilled project management workforce assignment across multiple projects regarding competency	O	SKILLS (competency-based assignment across projects), HUM-DYN (competency as explicit human-capital attribute)	—	OPT + simulation/framework evaluation; outputs: assignment quality/utilisation-style indicators (exact metrics not in snippet)	R-none
(Li et al., 2025) A multitasking workforce-constrained flexible job shop scheduling problem: An application from a real-world workshop	O	SKILLS (multi-skilled/multitasking workforce constraints in scheduling)	—	OPT (MILP + GA); outputs: makespan, total weighted tardiness	R-none
(Szwarc et al., 2024) Robust scheduling of multi-skilled workforce allocation: Job rotation approach	I–O	TEAM/ORG (job rotation explicitly as approach), HUM-DYN (learning/forgetting tied to rotation/competency evolution), SKILLS (multi-skilled allocation)	—	OPT (CSP) robust scheduling under unexpected events; outputs: schedule robustness/feasibility and project/work execution outcomes	R-explicit
(Abreu et al., 2023) Multiskilled labor force: a discussion of this missing link of lean construction in Brazilian companies	I–O	TEAM/ORG (adoption/implementation conditions discussed), SKILLS (multiskilling as lean lever)	COST/FEAS *(only to the extent barriers are discussed as implementation limits; you noted "barriers/enablers in firms")*	Discussion paper; reports benefits/barriers at conceptual level (reduced variability/waste, improved flow/productivity)	R-proxy
(Y. Li et al., 2007) An integrated staff-sizing approach considering feasibility of scheduling decision	I	COST/FEAS (feasibility of scheduling explicitly integrated into sizing)	—	OPT (multi-objective LP + procedure) ensuring feasible schedules; outputs: schedule feasibility/sizing performance	R-none
(Yoo et al., 2024) Illustrating the Anticipate, Recruit, Retain, Adapt, Sustain (ARRAS) framework for surge capacity. How Bangladesh, Sri Lanka, and Nepal	I–O	TEAM/ORG (recruit/retain/adapt/sustain strategies; incentives; coordination), SKILLS (re-skilling/upskilling/telemedicine noted),	—	Mixed-methods + descriptive trends; outputs: workforce maintenance trends (doctors/nurses) and framework mechanisms	R-explicit

maintained their health workforce during COVID-19		COORD (coordination mechanisms implied in framework)			
(Givi et al., 2015) Production planning in DRC systems considering worker performance	I–O	HUM-DYN (worker performance explicitly affects outcomes), SKILLS *(only if flexibility/transfer policies are explicit in the model; your note indicates transfer policy/configuration)*	—	Model-based comparative experiments; outputs: time-related cost + quality-related cost	R-proxy
(Attia et al., 2014) Considering skills evolutions in multi-skilled workforce allocation with flexible working hours	I–O	HUM-DYN (skill/experience evolution explicitly modelled), COST/FEAS (flexible working hours; overtime ratio; penalties) , SKILLS (multi-skilled allocation)	COST/FEAS (explicit penalties/ratios and "loss of future temporal flexibility" outputs)	OPT + GA; outputs: project penalty, overtime ratio, increase in working hours, loss of future temporal flexibility, experience evolution	R-none
(Coates et al., 2021) Health workforce strategies in response to major health events: a rapid scoping review with lessons learned for the response to the COVID-19 pandemic	I–O	TEAM/ORG (workforce capacity levers; barriers/facilitators), SKILLS (flexibility/scope expansion as lever)	—	Rapid scoping review; key note: many papers lack substantive evaluation; heterogeneous metrics	R-explicit
(Kelsey, 2006) Use 'em or lose 'em – The licensed practical nurse	I–O	TEAM/ORG (role redesign; acceptance/teamwork; job satisfaction), SKILLS (training/orientation tools; role utilisation)	—	Descriptive practice report; outcomes: job satisfaction, unit flexibility, teamwork	R-proxy
(Fægri et al., 2010) Introducing knowledge redundancy practice in software development: Experiences with job rotation in support work	I–O	TEAM/ORG (job rotation intervention in practice; organisational learning cycles), HUM-DYN *(only if treated as knowledge redundancy/competence distribution; your extraction highlights psychosocial measures)*	TEAM/ORG (burnout/role conflict/ambiguity measured as explicit frictions/risks)	Action research; outcomes: knowledge redundancy + burnout/role conflict/ambiguity indicators	R-proxy
(Henao et al., 2019) Multiskilled workforce management by utilizing closed chains under uncertain demand: A retail industry case	I–O	SKILLS (closed-chain multiskilling design), COORD *(only if reallocation/chain deployment rules are explicit; your extraction focuses more on design + evaluation)*	COST/FEAS (explicit staffing cost vs coverage trade-offs under uncertainty)	Three-stage method + Monte Carlo simulation + LP; outputs: robustness/performance under uncertain demand (coverage/service level vs cost)	R-proxy
(Mac-Vicar et al., 2017) Real-time recovering strategies on personnel scheduling in the retail industry	O	COORD (real-time recovery actions/algorithms), SKILLS (transfers of multiskilled employees as contingency resource)	TEAM/ORG (worker dissatisfaction from schedule modifications explicitly modelled)	OPT+HEU; disruptions: demand variations + unscheduled absences; outputs: lost profit + dissatisfaction proxy	R-proxy

(Spanier et al., 2021) Principles and practice of deploying a flexible physician workforce for COVID-19 care wards from a Dutch hospital	I–O	TEAM/ORG (principles for redeployment; transparency/solidarity; organisation), SKILLS (re-/upskilling and redeployment)	—	Practice/implementation report; outcome: surge capacity/continuity (qualitative)	R-explicit
(Xu et al., 2021) A vital layer of support: One safety net hospital's palliative care response to the pandemic	I–O	TEAM/ORG (rapid team reconfiguration; redeployment), SKILLS (targeted training of volunteers/redeployed providers)	—	Descriptive case report; outputs: activity/coverage counts (#patients served, #volunteers, etc.)	R-explicit
(Ebm et al., 2025) Return on investment of rapid ICU workforce upskilling: an economic and cost-effectiveness analysis	I	COST/FEAS (ROI/cost-effectiveness of upskilling explicitly quantified), SKILLS (upskilling intervention)	COST/FEAS (investment magnitude; break-even dependency via sensitivity analysis—treated explicitly as evaluation dimension)	Economic evaluation; outputs: ROI, break-even time, cost per participant, cost per QAHW, capacity expansion proxy	R-proxy
(Tsang et al., 2021) Blockchain-IoT-Driven nursing workforce planning for effective long-term care management in nursing homes	I–O	COORD (real-time monitoring/data system feeding staffing decisions), SKILLS (skill categories and flexibility), TEAM/ORG (workload balancing/QoC objective)	COST/FEAS (explicit cost minimisation under constraints; QoC–cost trade-off)	System + optimisation (IP/GA); outputs: max QoC at lowest cost; workload balance; staffing solution quality	R-proxy
(White et al., 2026) Voices from the bench: Focus group insights on shared research resource sustainability amid federal policy shifts	I–O	TEAM/ORG (leadership engagement + strategic integration of SRRs), COORD (multi-institutional collaboration + governance), SKILLS (cross-training + strategic recruitment), COST/FEAS (funding diversification + operational efficiency/standardized procurement)	COST/FEAS (federal funding cuts / indirect cost cap), TEAM/ORG (institutional silos, communication breakdowns), COORD (administrative/legal/compliance burdens; export control limits collaboration)	Focus groups (220+ leaders/staff): workforce adaptability via cross-training, shared staffing models; barriers include legal/HR/IT/contracting fragmentation; resilience framed as sustainability under policy uncertainty	R-explicit
(Lian et al., 2025) Valuing labor flexibility in cross-training using a real options approach	I	SKILLS (redundancy as "capacity buffer" via cross-training), COST/FEAS (real-options valuation to justify *when/how many* workers to train under uncertainty)	COST/FEAS (training-cost vs capacity-buffer trade-off), SKILLS (excessive multifunctionality reduces value; overtraining risk)	Stochastic DP + trinomial lattice: two-phase training plan; tests demand uncertainty, multi-skill level, penalty for unsatisfied demand; outputs: monetary value of flexibility and optimal training timing/volume	R-proxy
(Slomp et al., 2005) Cross-training in a cellular manufacturing environment	I (→ O via operating rules)	SKILLS (qualification "chains" to reallocate work), TEAM/ORG (workload balance + interpersonal justice/equity), COORD (need for appropriate operating rules)	COST/FEAS (very costly full flexibility; productivity loss due to worker shifts), TEAM/ORG (social identity/motivation risks; status effects)	IP model selects who-to-train-for-which-machine; explicit trade-off: training costs vs workload balance; rationale: handle fluctuations in demand mix and labor supply; discusses centralized vs decentralized assignment implications	R-proxy

(Nembhard et al., 2005) A real options model for workforce cross-training	I	SKILLS (dynamic cross-training investment), COST/FEAS (real options framework to value flexibility vs DCF/NPV), HUM-DYN (workforce heterogeneity explicitly moderates value)	COST/FEAS (irreversible investment risk under uncertainty), HUM-DYN (dependence on heterogeneity + production capability)	Real-options (American call option approximation) using binomial lattice; environment defined by product dynamics, labor dynamics, task heterogeneity, workforce heterogeneity; output: NPVRO vs NPVD (value increment of flexibility)	R-proxy
(Bokhorst et al., 2004) On the who-rule in Dual Resource Constrained (DRC) manufacturing systems	O	COORD (explicit *who-rule* for worker selection), HUM-DYN (task proficiency differences; skill breadth; workload responsibility differences)	COORD (assignment complexity; impact depends on utilization/load distribution), HUM-DYN (heterogeneity makes rule choice non-trivial)	SIM: shows why who-rule must be modelled at specific decision moments; explores flow-time effects across DRC systems; improvements depend on utilization and heterogeneity; reports significant WHO effects on flow time	R-proxy
(Sanders & Ritzman, 2004) Using warehouse workforce flexibility to offset forecast errors	O	SKILLS (degree of worker cross-training), TEAM/ORG (part-time labor buffer; flexible scheduling), COORD (short planning horizon + daily staffing logic)	COST/FEAS (forecast bias creates steep cost increases), TEAM/ORG (union/contract constraints restrict last-minute flexibility), HUM-DYN (efficiency loss + learning effects acknowledged as real-world limits)	SIM of public warehouse: forecast error decomposed into bias + standard deviation; tests flexibility measures (cross-training + part-time share); outcome = total organizational cost; flexibility buffers volatility more effectively for SD than for bias	R-proxy
(Hoyt & Matuszek, 2001) Testing the contribution of multi-skilled employees to the financial performance of high-tech organizations	I–O	SKILLS (multi-skilled workers / cross-training), TEAM/ORG (responsiveness & agility narrative as strategic rationale)	COST/FEAS (training & hiring costs may offset gains), TEAM/ORG (risk of "generalist" perception conflicting with specialist career goals)	Empirical test in three high-tech industries: MSW non-significant predictor of financial performance; authors explicitly caution that MSW benefits may be overstated or insufficient to outweigh associated costs	R-proxy
(Jensen, 2000) The impact of resource flexibility and staffing decisions on cellular and departmental shop performance	O	SKILLS (labor flexibility via cross-training), COORD (labor assignment/transfer rules), COST/FEAS (staffing level as a controllable design lever)	COST/FEAS (benefits depend strongly on staffing level; results highly sensitive to worker-to-machine ratio), U-type (demand variability moderates outcomes)	Simulation across layouts + staffing levels + workload balance: conclusions on flexibility trade-offs are very sensitive to staffing, somewhat to demand variability; under several conditions, emphasizing labor flexibility alone performs well	R-proxy
(Park & Bobrowski, 1989) Job release and labor flexibility in a dual resource constrained job shop	O	SKILLS (labor flexibility through cross-training), COORD (explicit job release mechanisms + labor assignment rules)	COST/FEAS (diminishing returns beyond minimum flexibility), COORD/COST (finite-loading accuracy decay and computational/implementation expense raised as practical concern)	DES experiment: release mechanisms × flexibility levels × assignment rules × due-date tightness; finding: minimum increment of flexibility yields greatest improvement and further flexibility shows diminishing returns	R-proxy
(Rochette & Sadowski, 1976) A statistical comparison of the performance of simple dispatching rules for a particular set of job shops	O	SKILLS (workforce flexibility explicitly improves performance), COORD (dispatching + staffing policies tested experimentally)	TEAM/ORG (union agreements explicitly constrain flexibility), HUM-DYN (efficiency decreases when workers switch centres), COST/FEAS	Simulation of real-world job shops (needle trades): workforce flexibility significantly improves mean flow time and mean tardiness across dispatching rules;	R-proxy

			(capacity limited by workforce size/flexibility and machine availability)	constraints explicitly attributed to union/efficiency/machine availability	
(Graham & Rosenthal, 1986) Flexible manufacturing systems require flexible people	I–O	TEAM/ORG (project team composition/experience; progressive people practices), COORD (in-house ↔ vendor relationships; cross-functional cooperation), SKILLS (cross-training, job rotation), HUM-DYN (continuing experimentation/adaptation)	TEAM/ORG (people policies often not considered early; narrow HR practice scope), COORD (poor alignment during procurement/planning leads to rework during start-up)	Multi-site fieldwork (8 companies): successful FMS adoption requires “flexible people”; emphasizes early attention to team structures, vendor coordination, workforce selection/training, and adaptive experimentation	R-none

Appendix 4. References

A. Nembhard, D. (2014). Cross training efficiency and flexibility with process change. *International Journal of Operations & Production Management*, *34*(11), 1417-1439. https://doi.org/10.1108/IJOPM-06-2012-0197

Abreu, J. P. M. de, Cardoso, G. de C., Marchiori, F. F., Brandstetter, M. C. G. de O., & Heineck, L. F. M. (2023). Multiskilled labor force: A discussion of this missing link of lean construction in Brazilian companies. *Ambiente Construído*, *23*(4), 7-23. https://doi.org/10.1590/s1678-86212023000400688

Altendorfer, K., Schober, A., Karder, J., & Beham, A. (2021). Service level improvement due to worker cross training with stochastic worker absence. *International Journal of Production Research*, *59*(14), 4416-4433. https://doi.org/10.1080/00207543.2020.1764126

Attia, E.-A., Duquenne, P., & Le-Lann, J.-M. (2014). Considering skills evolutions in multi-skilled workforce allocation with flexible working hours. *International Journal of Production Research*, *52*(15), 4548-4573. https://doi.org/10.1080/00207543.2013.877613

Ayough, A., Nouri, F. S., Khorshidvand, B., & Farhadi, F. (2025). Modeling workers rotation in divisional seru production systems. *Computers & Industrial Engineering*, 111141. https://doi.org/10.1016/j.cie.2025.111141

Azizi, N., & Liang, M. (2013). An integrated approach to worker assignment, workforce flexibility acquisition, and task rotation. *Journal of the Operational Research Society*, *64*(2), 260-275. https://doi.org/10.1057/jors.2012.30

Barkokebas, B., Al-Hussein, M., & Hamzeh, F. (2023). Assessment of digital twins to reassign multiskilled workers in offsite construction based on lean thinking. *Journal of Construction Engineering and Management*, *149*(1), 04022143. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002420

Bokhorst, J. A., Slomp, J., & Molleman, E. (2004). Development and evaluation of cross-training policies for manufacturing teams. *IIE Transactions*, *36*(10), 969-984. https://doi.org/10.1080/07408170490496209

Bokhorst, J., Slomp, J., & Gaalman, G. (2004). On the who-rule in dual resource constrained (DRC) manufacturing systems. *International Journal of Production Research*, *42*(23), 5049-5074. https://doi.org/10.1080/00207540410001733878

Chen, X., Li, K., Lin, S., & Ding, X. (2024). Technician routing and scheduling with employees' learning through implicit cross-training strategy. *International Journal of Production Economics*, *271*, 109208. https://doi.org/10.1016/j.ijpe.2024.109208

Coates, A., Fuad, A.-O., Hodgson, A., & Bourgeault, I. L. (2021). Health workforce strategies in response to major health events: A rapid scoping review with lessons learned for the response to the

COVID-19 pandemic. *Human resources for health*, *19*(1), 154. https://doi.org/10.1186/s12960-021-00698-6

Cuevas, R., Ferrer, J.-C., Klapp, M., & Muñoz, J.-C. (2016). A mixed integer programming approach to multi-skilled workforce scheduling. *Journal of Scheduling*, *19*(1), 91-106. https://doi.org/10.1007/s10951-015-0450-0

Daniels, R. L., Mazzola, J. B., & Shi, D. (2004). Flow shop scheduling with partial resource flexibility. *Management science*, *50*(5), 658-669. https://doi.org/10.1287/mnsc.1040.0209

De Sanctis, I., Ordieres Meré, J., & Ciarapica, F. E. (2018). Resilience for lean organisational network. *International Journal of Production Research*, *56*(21), 6917-6936. https://doi.org/10.1080/00207543.2018.1457810

Doan, M.-P., Fondrevelle, J., Botta-Genoulaz, V., & Ribeiro, J. F. (2022). Impact of flexible work contracts and multi-skilled agents on a multi-objective workforce planning problem. *International Journal of Production Research*, *60*(5), 1650-1665. https://doi.org/10.1080/00207543.2020.1867922

Easton, F. F. (2011). Cross-training performance in flexible labor scheduling environments. *IIE Transactions*, *43*(8), 589-603. https://doi.org/10.1080/0740817X.2010.550906

Ebm, C., Istrate, M., Van Gelder, F., Szőllősi, G. J., Alexandre, J., Azoulay, E., Kesecioglu, J., & Cecconi, M. (2025). Return on investment of rapid ICU workforce upskilling: An economic and cost-effectiveness analysis. *Intensive Care Medicine*, *51*(8), 1453-1461. https://doi.org/10.1007/s00134-025-08033-6

Fægri, T. E., Dybå, T., & Dingsøyr, T. (2010). Introducing knowledge redundancy practice in software development: Experiences with job rotation in support work. *Information and Software Technology*, *52*(10), 1118-1132. https://doi.org/10.1016/j.infsof.2010.06.002

Felan, J. T., & Fry, T. D. (2001). Multi-level heterogeneous worker flexibility in a Dual Resource Constrained (DRC) job-shop. *International journal of production research*, *39*(14), 3041-3059. https://doi.org/10.1080/00207540110047702

Felan, J. T., Fry, T. D., & Philipoom, P. R. (1993). Labour flexibility and staffing levels in a dual-resource constrained job shop. *International Journal of Production Research*, *31*(10), 2487-2506. Scopus. https://doi.org/10.1080/00207549308956871

Ferjani, A., Ammar, A., Pierreval, H., & Elkosantini, S. (2017). A simulation-optimization based heuristic for the online assignment of multi-skilled workers subjected to fatigue in manufacturing systems. *Computers & Industrial Engineering*, *112*, 663-674. https://doi.org/10.1016/j.cie.2017.02.008

Fernandes, N. O., Thürer, M., Rodrigues, F., Ferreira, L. P., Silva, F. J., & Ávila, P. (2022). Worker assignment in dual resource constrained systems subject to machine failures: A simulation

study. *International Journal of Industrial Engineering and Management*, *13*(2), 110-118. https://doi.org/10.24867/IJIEM-2022-2-305

Fraser, K., & Hvolby, H.-H. (2010). Effective teamworking:Can functional flexibility act as an enhancing factor?an Australian case study. *Team Performance Management*, *16*(1-2), 74-94. Scopus. https://doi.org/10.1108/13527591011028933

Gel, E. S., Hopp, W. J., & Van Oyen, M. P. (2007). Hierarchical cross-training in work-in-process-constrained systems. *IIE Transactions*, *39*(2), 125-143. https://doi.org/10.1080/07408170600729184

Givi, Z., Jaber, M. Y., & Neumann, W. P. (2015). Production planning in DRC systems considering worker performance. *Computers & Industrial Engineering*, *87*, 317-327. https://doi.org/10.1016/j.cie.2015.05.005

Gnanlet, A., & Gilland, W. G. (2014). Impact of productivity on cross-training configurations and optimal staffing decisions in hospitals. *European Journal of Operational Research*, *238*(1), 254-269. https://doi.org/10.1016/j.ejor.2014.03.033

Graham, M. B., & Rosenthal, S. R. (1986). Flexible manufacturing systems require flexible people. *Human Systems Management*, *6*(3), 211-222. https://doi.org/10.3233/HSM-1986-6304

Grant, K., & Hallam, C. (2016). Team performance in a lean manufacturing operation: It takes the will and a way to succeed. *International Journal of Technology Management*, *70*(2-3), 177-192. (WOS:000372100000004). https://doi.org/10.1504/IJTM.2016.075161

Han, J., Chen, C., Tiong, R. L. K., Wu, K., & Chew, D. K. H. (2024). Strategic Workforce Planning for Production of Prefabricated Bathroom Units: An Advanced Markovian Approach. *Journal of Construction Engineering and Management*, *150*(8), 04024097. https://doi.org/10.1061/JCEMD4.COENG-14514

Henao, C. A., Batista, A., Porto, A. F., & González, V. I. (2022). Multiskilled personnel assignment problem under uncertain demand: A benchmarking analysis. *Math. Biosci. Eng*, *19*(5), 4946-4975. https://doi.org/10.3934/mbe.2022232

Henao, C. A., Ferrer, J. C., Muñoz, J. C., & Vera, J. (2016). Multiskilling with closed chains in a service industry: A robust optimization approach. *International Journal of Production Economics*, *179*, 166-178. https://doi.org/10.1016/j.ijpe.2016.06.013

Henao, C. A., Mercado, Y. A., González, V. I., & Lüer-Villagra, A. (2023). Multiskilled personnel assignment with k-chaining considering the learning-forgetting phenomena. *International Journal of Production Economics*, *265*, 109018. https://doi.org/10.1016/j.ijpe.2023.109018

Henao, C. A., Muñoz, J. C., & Ferrer, J. C. (2015). The impact of multi-skilling on personnel scheduling in the service sector: A retail industry case. *Journal of the Operational Research Society*, *66*(12), 1949-1959. https://doi.org/10.1057/jors.2015.9

Henao, C. A., Muñoz, J. C., & Ferrer, J. C. (2019). Multiskilled workforce management by utilizing closed chains under uncertain demand: A retail industry case. *Computers & Industrial Engineering*, *127*, 74-88. https://doi.org/10.1016/j.cie.2018.11.061

Heyhat, S., Rahmani, D., & Shahparvari, S. (2026). Data-driven distributionally robust optimization for resilient healthcare resource planning and crisis mitigation. *Transportation Research Part E: Logistics and Transportation Review*, *205*, 104449. https://doi.org/10.1016/j.tre.2025.104449

Hopp, W. J., Iravani, S. M., Shou, B., & Lien, R. (2009). Design and control of agile automated CONWIP production lines. *Naval Research Logistics (NRL)*, *56*(1), 42-56. https://doi.org/10.1002/nav.20325

Hopp, W. J., & Oyen, M. P. (2004). Agile workforce evaluation: A framework for cross-training and coordination. *Iie Transactions*, *36*(10), 919-940. https://doi.org/10.1080/07408170490487759

Hopp, W. J., Tekin, E., & Van Oyen, M. P. (2004). Benefits of skill chaining in serial production lines with cross-trained workers. *Management Science*, *50*(1), 83-98. https://doi.org/10.1287/mnsc.1030.0166

Hoyt, J., & Matuszek, T. (2001). Testing the contribution of multi-skilled employees to the financial performance of high-tech organizations. *The Journal of High Technology Management Research*, *12*(2), 167-181. https://doi.org/10.1016/S1047-8310(01)00043-8

Iravani, S. M., & Krishnamurthy, V. (2007). Workforce agility in repair and maintenance environments. *Manufacturing & Service Operations Management*, *9*(2), 168-184. https://doi.org/10.1287/msom.1060.0132

Iravani, S. M., Van Oyen, M. P., & Sims, K. T. (2005). Structural flexibility: A new perspective on the design of manufacturing and service operations. *Management Science*, *51*(2), 151-166. https://doi.org/10.1287/mnsc.1040.0333

Jensen, J. B. (2000). The impact of resource flexibility and staffing decisions on cellular and departmental shop performance. *European Journal of Operational Research*, *127*(2), 279-296. https://doi.org/10.1016/S0377-2217(99)00491-9

Jordan, W. C., Inman, R. R., & Blumenfeld, D. E. (2004). Chained cross-training of workers for robust performance. *IIE Transactions*, *36*(10), 953-967. https://doi.org/10.1080/07408170490487713

Julie Yazici, H. (2005). Influence of flexibilities on manufacturing cells for faster delivery using simulation. *Journal of Manufacturing Technology Management*, *16*(8), 825-841. https://doi.org/10.1108/17410380510627843

Kelsey, L. R. (2006). Use'em or lose'em: The licensed practical nurse. *Gastroenterology Nursing*, *29*(1), 37-41. https://doi.org/10.1177/0840470416633237

Kim, S., & Nembhard, D. A. (2010). Cross-trained staffing levels with heterogeneous learning/forgetting. *IEEE Transactions on Engineering Management*, *57*(4), 560-574. https://doi.org/10.1109/TEM.2010.2048905

Kim, S., & Nembhard, D. A. (2013). Rule mining for scheduling cross training with a heterogeneous workforce. *International Journal of Production Research*, *51*(8), 2281-2300. https://doi.org/10.1080/00207543.2012.716169

Li, J., Li, X., Gao, L., Wang, C., & Chen, H. (2025). A multitasking workforce-constrained flexible job shop scheduling problem: An application from a real-world workshop. *Journal of Manufacturing Systems*, *83*, 196-215. https://doi.org/10.1016/j.jmsy.2025.09.004

Li, Y., Chen, J., & Cai, X. (2007). An integrated staff-sizing approach considering feasibility of scheduling decision. *Annals of Operations Research*, *155*(1), 361-390. https://doi.org/10.1007/s10479-007-0215-z

Lian, J., Liu, C., Xu, Y., & Li, Y. (2025). Valuing labor flexibility in cross-training using a real options approach. *Flexible Services and Manufacturing Journal*, 1-21. https://doi.org/10.1007/s10696-025-09610-z

Mac-Vicar, M., Ferrer, J. C., Muñoz, J. C., & Henao, C. A. (2017). Real-time recovering strategies on personnel scheduling in the retail industry. *Computers & Industrial Engineering*, *113*, 589-601. https://doi.org/10.1016/j.cie.2017.09.045

McCreery, J. K., & Krajewski, L. J. (1999). Improving performance using workforce flexibility in an assembly environment with learning and forgetting effects. *International Journal of Production Research*, *37*(9), 2031-2058. https://doi.org/10.1080/002075499190897

McCreery, J. K., Krajewski, L. J., Leong, G. K., & Ward, P. T. (2004). Performance implications of assembly work teams. *Journal of Operations Management*, *22*(4), 387-412. https://doi.org/10.1016/j.jom.2004.05.004

Mou, S. (2022). Integrated order picking and multi-skilled picker scheduling in omni-channel retail stores. *Mathematics*, *10*(9), 1484. https://doi.org/10.3390/math10091484

Mou, S., & Robb, D. J. (2019). Real-time labour allocation in grocery stores: A simulation-based approach. *Decision Support Systems*, *124*, 113095. https://doi.org/10.1016/j.dss.2019.113095

Nembhard, D. A., Nembhard, H. B., & Qin, R. (2005). A real options model for workforce cross-training. *The Engineering Economist*, *50*(2), 95-116. https://doi.org/10.1080/00137910590949850

Olivella, J., & Nembhard, D. (2016). Calibrating cross-training to meet demand mix variation and employee absence. *European Journal of Operational Research*, *248*(2), 462-472. https://doi.org/10.1016/j.ejor.2015.07.036

Olivella, J., & Nembhard, D. (2017). Cross-training policies for team cost and robustness. *Computers & Industrial Engineering*, *111*, 79-88. https://doi.org/10.1016/j.cie.2017.07.006

Park, P. S. (1991). The examination of worker cross-training in a dual resource constrained job shop. *European Journal of Operational Research*, *52*(3), 291-299. https://doi.org/10.1016/0377-2217(91)90164-Q

Park, P. S., & Bobrowski, P. M. (1989). Job release and labor flexibility in a dual resource constrained job shop. *Journal of operations management*, *8*(3), 230-249. https://doi.org/10.1016/0272-6963(89)90026-0

Porto, A. F., Henao, C. A., López-Ospina, H., & González, E. R. (2019). Hybrid flexibility strategy on personnel scheduling: Retail case study. *Computers & Industrial Engineering*, *133*, 220-230. https://doi.org/10.1016/j.cie.2019.04.049

Porto, A. F., Henao, C. A., Lusa, A., Mejía, O. P., & Solano, R. P. (2022). Solving a staffing problem with annualized hours, multiskilling with 2-chaining, and overtime: A retail industry case. *Computers & Industrial Engineering*, *167*, 107999. https://doi.org/10.1016/j.cie.2022.107999

Porto, A. F., Lusa, A., Herazo, S. A., & Henao, C. A. (2025). Improving the robustness of retail workforce management with a labor flexibility strategy and consideration of demand uncertainty. *Operations Research Perspectives*, *15*, 100345. https://doi.org/10.1016/j.orp.2025.100345

Rochette, R., & Sadowski, R. P. (1976). A statistical comparison of the performance of simple dispatching rules for a particular set of job shops. *The International Journal of Production Research*, *14*(1), 63-75. http://dx.doi.org/10.1080/00207547608956580

Sanders, N. R., & Ritzman, L. P. (2004). Using warehouse workforce flexibility to offset forecast errors. *Journal of Business Logistics*, *25*(2), 251-269. https://doi.org/10.1002/j.2158-1592.2004.tb00189.xDigital%20Object%20Identifier%20(DOI)

Sarihi, M., Shahhosseini, V., & Banki, M. T. (2020). Multiskilled project management workforce assignment across multiple projects regarding competency. *Journal of Construction Engineering and Management*, *146*(12), 04020134. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001938

Sawhney, R. (2013). Implementing labor flexibility: A missing link between acquired labor flexibility and plant performance. *Journal of Operations Management*, *31*(1-2), 98-108. (WOS:000315306700010). https://doi.org/10.1016/j.jom.2012.11.003

Slomp, J., Bokhorst, J. A., & Molleman, E. (2005). Cross-training in a cellular manufacturing environment. *Computers & Industrial Engineering*, *48*(3), 609-624. https://doi.org/10.1016/j.cie.2003.03.004

Slomp, J., & Molleman, E. (2002). Cross-training policies and team performance. *International Journal of Production Research*, *40*(5), 1193-1219. https://doi.org/10.1080/00207540110098823

Slomp, J., & Suresh, N. C. (2005). The shift team formation problem in multi-shift manufacturing operations. *European Journal of Operational Research*, *165*(3), 708-728. https://doi.org/10.1016/j.ejor.2004.01.034

Spanier, M., Kerkvliet, K., & Veeman, A. (2021). Principles and practice of deploying a flexible physician workforce for COVID-19 care wards from a Dutch hospital. *Future Healthcare Journal*, *8*(2), e311-e313. https://doi.org/10.7861/fhj.2020-0254

Stewart, B., Webster, D., Ahmad, S., & Matson, J. (1994). Mathematical models for developing a flexible workforce. *International Journal of Production Economics*, *36*(3), 243-254. https://doi.org/10.1016/0925-5273(94)00033-6

Suresh, N. C., & Slomp, J. (2005). Performance comparison of virtual cellular manufacturing with functional and cellular layouts in DRC settings. *International Journal of Production Research*, *43*(5), 945-979. https://doi.org/10.1080/00207540412331320508

Szwarc, E., Golińska-Dawson, P., Bocewicz, G., & Banaszak, Z. (2024). Robust scheduling of multi-skilled workforce allocation: Job rotation approach. *Electronics*, *13*(2), 392. https://doi.org/10.3390/electronics13020392

Tian, B., Kaul, H., & Janardhanan, M. (2024). Balancing heterogeneous assembly line with multi-skilled human-robot collaboration via Adaptive cooperative co-evolutionary algorithm. *Swarm and Evolutionary Computation*, *91*, 101762. https://doi.org/10.1016/j.swevo.2024.101762

Tiwari, M., & Roy, D. (2002). Application of an evolutionary fuzzy system for the estimation of workforce deployment and cross-training in an assembly environment. *International Journal of Production Research*, *40*(18), 4651-4674. https://doi.org/10.1080/00207540210158014

Tsang, Y., Wu, C., Leung, P. P., Ip, W., & Ching, W. (2021). Blockchain-IoT-driven nursing workforce planning for effective long-term care management in nursing homes. *Journal of healthcare engineering*, *2021*(1), 9974059. https://doi.org/10.1155/2021/9974059

Turan, H. H., Kosanoglu, F., & Atmis, M. (2021). A multi-skilled workforce optimisation in maintenance logistics networks by multi-thread simulated annealing algorithms. *International Journal of Production Research*, *59*(9), 2624-2646. https://doi.org/10.1080/00207543.2020.1735665

Valeva, S., Hewitt, M., Thomas, B. W., & Brown, K. G. (2017). Balancing flexibility and inventory in workforce planning with learning. *International Journal of Production Economics*, *183*, 194-207. https://doi.org/10.1016/j.ijpe.2016.10.026

Van Oyen, M. P., Gel, E. G., & Hopp, W. J. (2001). Performance opportunity for workforce agility in collaborative and noncollaborative work systems. *IIE Transactions*, *33*(9), 761-777. https://doi.org/10.1023/A:1010997816249

White, A., Ingersoll, R., Eswaraka, J., Uthamanthil, R., Roble, G., Chitty, A., Nikolaidis, N., Vinard, A., Kraft, M., & Winter, M. (2026). Voices from the Bench: Focus Group Insights on Shared Research

Resource Sustainability Amid Federal Policy Shifts. *Journal of Biomolecular Techniques: JBT*, *36*(4), 25. https://doi.org/10.7171/001c.153858

Wise, S., Duffield, C., Fry, M., & Roche, M. (2020). Clarifying workforce flexibility from a division of labor perspective: A mixed methods study of an emergency department team. *Human resources for health*, *18*(1), 17. https://doi.org/10.1186/s12960-020-0460-7

Wu, L., Cai, F., Li, L., & Chu, X. (2018). Cross-Trained Worker Assignment Problem in Cellular Manufacturing System Using Swarm Intelligence Metaheuristics. *Mathematical Problems in Engineering*, *2018*(1), 4302062. https://doi.org/10.1155/2018/4302062

Xu, Y., Zhang, L. K., Smeltz, R. L., & Cohen, S. E. (2021). A Vital Layer of Support: One Safety Net Hospital's Palliative Care Response to the Pandemic. *Journal of Palliative Medicine*, *24*(10), 1474-1480. https://doi.org/10.1089/jpm.2020.057

Yang, K.-K., Webster, S., & Ruben, R. A. (2007). An evaluation of worker cross training and flexible workdays in job shops. *IIE Transactions*, *39*(7), 735-746. https://doi.org/10.1080/07408170701244687

Yoo, K. J., Mannan, M., Weerasinghe, I., Borse, N. N., & Bishai, D. (2024). Illustrating the Anticipate, Recruit, Retain, Adapt, Sustain (ARRAS) Framework for Surge Capacity. How Bangladesh, Sri Lanka, and Nepal Maintained Their Health Workforce During COVID-19. *Disaster medicine and public health preparedness*, *18*, e217. https://doi.org/10.1017/dmp.2024.261

Zelenyanszki, C., Vertenten, C., Spencer, S., Hudson, D., & Currie, R. (2022). Extending the scope of practice for experienced assistant practitioners in breast screening and the impact on service resilience. *Radiography*, *28*(4), 973-980. https://doi.org/10.1016/j.radi.2022.06.021