A Systematic Literature Review of Hybrid Biased Random-Key Genetic Algorithms and Tabu Search for Job Shop Scheduling with Continuous Flow Transporters

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Abstract

This paper presents a systematic literature review (SLR) on the hybridization of Biased Random-Key Genetic Algorithms and Tabu Search for optimizing the Job Shop Scheduling Problem under conveyor-based Continuous Flow Transport constraints. The study maps the synergistic capability of Hybrid Metaheuristics in evolutionary exploration and local exploitation within highly synchronized manufacturing environments characterized by First-In, First-Out (FIFO) rules and limited buffer capacities. Following a protocol-driven methodology, the study analyzes peer-reviewed literature from Scopus and ScienceDirect databases indexed between 2015 and 2025. The synthesis of algorithmic strategies reveals a significant gap in explicitly tailored, decoder-centric hybrid frameworks for CFT-JSSP. Consequently, this review establishes a strategic research agenda focused on integrating advanced global-local search structures and problem-aware decoders to optimize makespan minimization and system resilience in flexible manufacturing ecosystems.

Keywords: *Job Shop Scheduling Problem, Continuous Flow Transport, Biased Random-Key Genetic Algorithm, Tabu Search, Hybrid Metaheuristics.*

1. Introduction

The Job Shop Scheduling Problem (JSSP) is a fundamental and important combinatorial optimization problem with applications ranging from operations research and management science to production planning and manufacturing (Xiong et al., 2022). It is traditionally characterized by the allocation of jobs to be carried out on various machines, where each job consists of one or more processes called operation/s carried out in a predetermined order (sequence) and on a particular machine to optimize an objective function, typically minimizing the makespan (C_{max}) (Momenikorbekandi & Kalganova, 2025).

JSSP is classified as NP-hard, implying that the search for a globally optimal solution using only exact methods becomes computationally infeasible for large-scale instances (Danach et al., 2025). The classical JSSP is traditionally governed by job-flow precedence, machine capacity, and non-preemption constraints. However, as modern manufacturing evolves toward automation and system integration, the conventional assumptions of infinite logistical resources or negligible transit intervals are no longer tenable. Consequently, it is now imperative to integrate additional operational variables, specifically transportation latency, buffer limitations, blocking phenomena, and rigid flow sequencing, into the scheduling framework.

In modern flexible manufacturing systems, particularly within the electronics and semiconductor industries, the conveyor-based Continuous Flow Transporter (CFT) is gaining momentum to emerge as the primary mechanism for material handling (Nazzal & El-Nashar, 2007; Schwenke & Kabitzsch, 2017). Unlike Automated Guided Vehicles (AGVs), which offer high degrees of path flexibility, conveyor systems impose rigid physical and logical constraints. The most pervasive of these constraints are the First-In, First-Out (FIFO) rule and limited inter-machine buffer capacities(Fan & Su, 2022). Such constraints necessitate a high degree of synchronization, as the temporal entry of a job onto a conveyor segment determines its downstream processing sequence. This dependency effectively merges transport logistics with production scheduling into a singular, integrated optimization problem.

The research problem addressed in this systematic literature review focuses on the current state of the art regarding the application of hybrid metaheuristics, specifically the hybridization of Biased Random-Key Genetic Algorithms (BRKGA) and Tabu Search (TS), to solve the CFT-JSSP. BRKGA is widely recognized for its robust global exploration capabilities and its ability to search continuous spaces through random-key encoding, while maintaining feasibility via problem-specific decoders(Londe, Andrade, et al., 2025; Silva et al., 2023).

Conversely, Tabu Search excels at intensive local exploitation, utilizing memory-based mechanisms to refine solution quality in the proximity of promising regions(Taillard, 2023). The synergy between these two metaheuristics is hypothesized to be particularly effective in navigating the constrained landscapes imposed by CFT systems, where small permutations in job sequences can have cascading effects on system blocking and machine starvation.

The primary objective of this study is to critically examine the existing modeling approaches, algorithmic strategies, and empirical evaluations pertinent to hybrid BRKGA-TS frameworks for CFT-JSSP. By synthesizing literature from Scopus-indexed journals, this report aims to answer three key research questions:

(RQ1) What are the dominant modeling paradigms for JSSP under CFT constraints?

(RQ2) How have hybrid BRKGA and TS methodologies been integrated for complex scheduling challenges?

(RQ3) What are the specific research gaps that inhibit the practical deployment of these hybrids in conveyor-constrained environments?

The rationale for this review lies in the need for more sophisticated, decoder-centric algorithmic designs that can translate the theoretical strengths of evolutionary search into robust, feasible schedules for automated shop floors.

2. Theoretical Framework

The investigation of JSSP within the context of Conveyor-based Continuous Flow Transport requires a multidisciplinary framework that bridges combinatorial optimization, control theory, and industrial logistics.

2.1. Formal Definition of JSSP and the Job-Machine Matrix

The JSSP is formally described as a set of $\boldsymbol{'n'}$ jobs $J = J_1, J_2, \dots, J_n$, to be processed on a set $\boldsymbol{'m'}$ machines $M = M_1, M_2, \dots, M_m$. Each job J_i consists of a sequence of operations $O = O_{i,1}, O_{i,2}, \dots, O_{i,m}$ that must be performed in a predetermined order(Hoss et al., 2025; Rihane et al., 2025). Each operation, denoted as $\boldsymbol{O_{ij}}$ for job $\boldsymbol{J_i}$, is assigned to a particular machine $\boldsymbol{M_k}$ and requires a defined processing time $\boldsymbol{P_{ij}}$ as represented by the matrix in Figure 1.

Figure 1 – Job-Machine Matrix Representation for JSSP

Machines

Jobs	M_1	M_2	M_3	$\cdots$	M_m
J_1	O_{11}, P_{11}	O_{12}, P_{12}	O_{13}, P_{13}	$\cdots$	O_{1m}, P_{1m}
J_2	O_{21}, P_{21}	O_{22}, P_{22}	O_{23}, P_{23}	$\cdots$	O_{2m}, P_{2m}
J_3	O_{31}, P_{31}	$\cdots$	$\cdots$	$\cdots$	$\cdots$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
J_n	O_{n1}, P_{n1}	O_{n2}, P_{n2}	$\cdots$	$\cdots$	O_{nm}, P_{nm}

Source: Author (2025)

The constraints governing the classical JSSP include:

(i) each machine can process only one operation at a time,

(ii) operations cannot be pre-empted once started, and

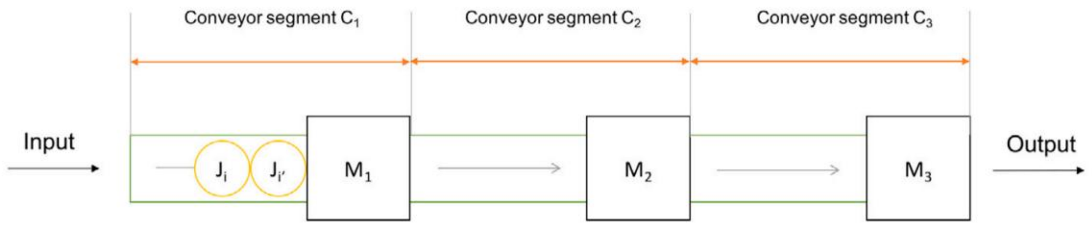
(iii) the precedence constraints within each job must be strictly maintained, such that $S_{i,j+1} \geq C_{i,j}$ where $S_{i,j}$ and $C_{i,j}$ denotes start and completion times, respectively.

In the presence of CFT, the completion time $C_{i,j}$ must also account for the transport time and potential blocking durations.

2.2. Characteristics of Conveyor-Based Continuous Flow Transport

In the CFT-JSSP framework, jobs are not merely processed by a sequence of machines but are also conveyed via a continuous flow transporter (CFT), as illustrated in Figure 2. This architecture necessitates the integration of the conveyor as an explicit resource, denoted as $\boldsymbol{C} = \{\boldsymbol{c_k}\}_{\boldsymbol{k=1}}^{\boldsymbol{m}}$, within the formal problem definition. The complexity of the CFT-JSSP arises primarily from two interlocking constraints: the First-In, First-Out (FIFO) protocol and finite buffer capacities. Unlike the classical JSSP, where job sequences may be independently optimized for each machine, the FIFO rule dictates that the relative entry order must be strictly preserved throughout the transport segment. Furthermore, restricted buffering imposes a physical ceiling on the queue at each workstation, significantly intensifying the challenge of generating feasible schedules while avoiding system-wide congestion (Dong et al., 2025; Fan & Su, 2022).

Figure 2 – Layout of machines and Conveyors in a simple CFT shop



Source: Adapted from Fan & Su (2022)

The operational dynamics of the conveyor-based system are governed by three fundamental parameters that dictate the physical and logical flow of entities (Khayat et al., 2006; Lim & Moon, 2023):

1. FIFO Constraint: The relative order of jobs entering a conveyor segment must be preserved until they exit. formally, for any two jobs J_i and $J_{i'}$,

$$EntryTime\ (J_i\ ) < EntryTime\ (J_{i'}\ ) \underset{implies}{\Longrightarrow} ExitTime\ (J_i\ )\ < ExitTime\ (J_{i'}\ )$$

2. Limited Buffer Capacity: Each machine station has a finite buffer space for jobs waiting for processing. If the buffer is full (b_{max} *is acheived*), the conveyor segment upstream is blocked, potentially causing a 'blocking-after-service' state where the preceding machine cannot release its completed job.

3. Transport Time: The non-negligible transport times ($T_{i,j} > 0$) required to move between machines, which must be incorporated into the temporal dependencies of the schedule, increase ($Minimizing\ C_{max}$) calculation complexity.

Table 1 – Operational constraints and their impact on optimization in CFT-JSSP environments

Problem Element	Technical Description (CFT Context)	Impact on Optimization
Flow Topology	Fixed physical linkages between workstations via conveyor segments.	Constrains the feasible technological routes relative to the flexibility of AGVs.
FIFO Protocol	Mandatory preservation of job sequences during transit.	Induces a serial dependency between the start times of successive machine operations.
Conveyor Buffering	Finite capacity dictated by the physical dimensions of the transport segment.	Triggers upstream propagation of blocking phenomena (Blocking-after-service).

Transport Latency	Deterministic function of conveyor velocity and spatial displacement.	Introduces a non-zero temporal component to the makespan, requiring global synchronization.

Source: Compiled by Author(2025)

2.3. The Biased Random-Key Genetic Algorithm (BRKGA)

The BRKGA is a population-based evolutionary optimization method designed for combinatorial problems whose solutions can be expressed as permutations (Gonçalves & Resende, 2011). Unlike standard genetic algorithms that operate directly on problem-specific representations (e.g., job sequences), BRKGA operates on a continuous space of random keys, vectors of real numbers in the interval $[0, 1)$ (Londe, Pessoa, et al., 2025; Stefanello et al., 2015).

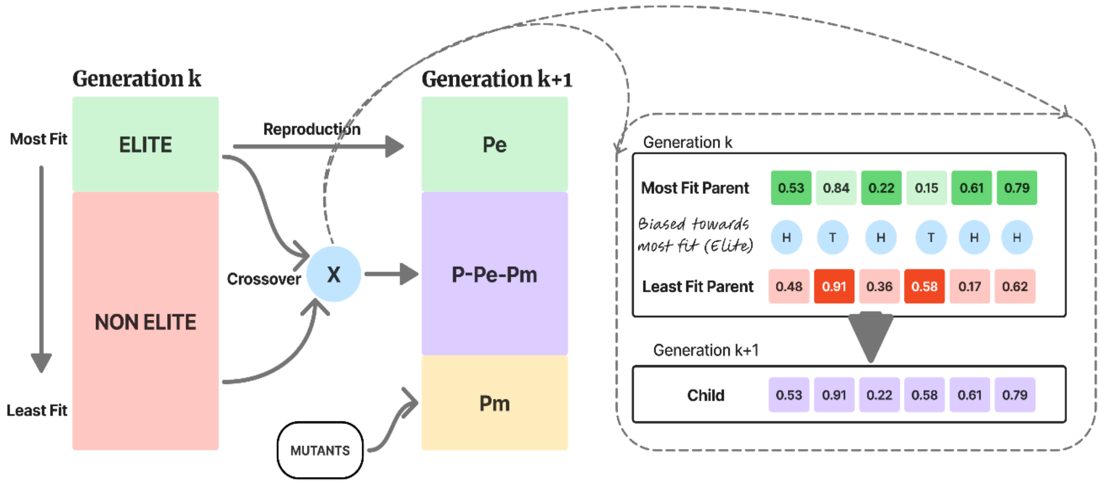
The evolutionary process of BRKGA involves the following core components:

- Population Partitioning: In each generation, the population p is divided into a small set of elite individuals p_e (the most fit) and a non-elite set $p - p_e$.
- Reproduction: The elite individuals are copied directly to the next generation, ensuring that high-quality genetic material is never lost.
- Biased Crossover: Offspring population portion $(p - p_e - p_m)$ is generated by mating an elite parent with a non-elite parent. A probability ρ (typically $\rho > 0.5$) is assigned to inheriting the gene from the elite parent, which guides the search toward promising regions.
- Mutants: To maintain diversity and prevent premature convergence, a portion (p_m) of the population in each generation consists of "mutants", randomly generated vectors.

This evolutionary process is visually represented in Figure 3.

In the context of CFT-JSSP, the bridge between the random keys and a feasible schedule is the decoder, a deterministic algorithm that interprets the priority values represented by the keys to build a schedule while respecting CFT constraints.

Figure 3: Evolutionary process between consecutive generations



Source: Adopted from Londe et al., (2023)

2.4. Tabu Search and Neighborhood Search Operators

Tabu Search (TS) is a powerful local search metaheuristic that overcomes the limitations of simple hill-climbing by using adaptive memory to escape local optima(Glover et al., 2018). At each iteration, the algorithm moves to the best neighboring solution, even if that move results in a temporary worsening of the objective function(KADDOURI & OMARY, 2017).

The effectiveness of TS for JSSP depends on the neighborhood structure, which defines the set of solutions reachable through a single "move". Standard neighborhoods like N5, N6, and N7 focus on swapping or reinserting operations within a critical block (Taillard, 2023). However, for CFT-JSSP, moves must account for the impact on downstream buffers and transport synchronization.

Tabu Search employs an aspiration criterion for flexibility, as well as strategies for intensification and diversification. It uses a tabu list on move attributes and aspiration to accept improving tabu moves. This step exploits the local structure that the BRKGA cannot easily refine (Nowicki & Smutnicki, 1996). Its main weakness is sensitivity to the initial solution, potentially leading to suboptimal results. This limitation is the precise problem that a global search algorithm, such as BRKGA, is designed to address, creating a compelling case for their integration (Thamilselvan & Balasubramanie, 2009).

3. Methodology

This systematic literature review follows a protocol-driven methodology to ensure transparency, reproducibility, and academic rigor. The approach integrates a structured funnel filter selection process for qualitative research synthesis.

3.1. Research Protocol and Information Retrieval

The review was conducted using peer-reviewed journal articles and high-quality conference papers indexed in Scopus, ScienceDirect, IEEE Xplore, and Web of Science, covering the decade from 2015 to 2025. The research protocol was established to address the three primary research questions (RQs) regarding modeling, algorithmic hybridization, and gap identification.

Table 2 – Research protocol for the SLR

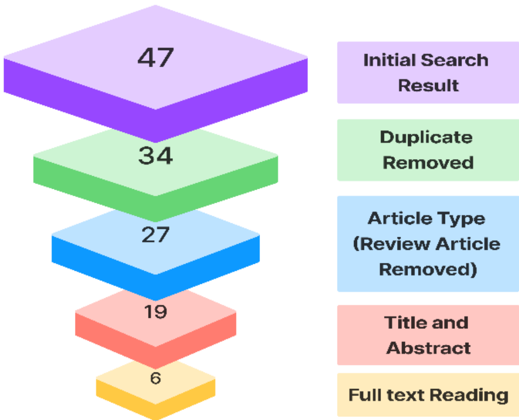
Component	**Detail**
Search String	*("Job Shop Scheduling Problem" OR "JSP" OR "JSSP") AND ("Biased Random Key Genetic Algorithm" OR "BRKGA") AND ("Tabu Search" OR "Local Search") AND ("Continuous Flow Transporter" OR "CFT" OR "Conveyor System").*
Databases	Scopus, ScienceDirect, IEEE Xplore, Web of Science
Timeframe	2015 – 2025
Document Type	Journal Articles and Conference Papers
Language	English
Inclusion Criteria	Studies focusing on JSSP or FJSP; studies addressing CFT or conveyors; studies discussing hybrid BRKGA and TS
Exclusion Criteria	Studies on other scheduling problems (e.g., Openshop) unless methodology is relevant; duplicate publications

Source: Author (2025)

The systematic search was conducted using two distinct string configurations. An initial, highly restrictive string, comprising 'Job Shop Scheduling Problem,' 'Biased Random-Key Genetic Algorithm,' 'Tabu Search,' and 'Continuous Flow Transporter', yielded no results across the four targeted databases, even when tested with various logical concatenations. Consequently, the scope was broadened to include terms such as 'Hybrid Metaheuristic,' 'Job Shop Scheduling Problem,' and 'Conveyor.' Inclusion criteria were strictly defined to prioritize studies integrating genetic algorithms with local search within conveyor-based JSSP variants. Conversely, exclusion criteria eliminated unrelated scheduling models, secondary reviews, and duplicate entries.

The filtering process, as shown in Figure 4, is carried out to identify the most relevant studies. The refined search strategy retrieved 47 documents (30 from ScienceDirect and 17 from Scopus); the higher yield from ScienceDirect is attributable to its comprehensive full-text search capabilities relative to Scopus's metadata-centric indexing. Following the removal of 13 duplicates and an initial title/abstract screening, 19 candidates underwent a rigorous full-text evaluation, resulting in the final selection of 6 core articles directly addressing the BRKGA-TS/CFT-JSSP intersection.

Figure 4 – Stages of filtering the relevant resource



Fonte: Author (2025)

4. Result and Discussion

The synthesis of literature reveals a sophisticated landscape of scheduling research where the focus has transitioned from simple efficiency to complex synchronization.

4.1. Comparative Analysis of State-of-the-Art Research

The selected articles demonstrate a diversity of approaches to the JSSP across various transport and material-handling configurations.

Table 3 – Synthesis of core literature findings

Author(s) & Year	Problem Context	Logistics & Handling Mechanism	Algorithmic Framework	Key Optimization Outcomes	Relevance to BRKGA-TS/CFT
Lopez-Juarez et al. (2024)	Flexible Job Shop (FJSSP)	Conveyor belts & robotic manipulators	Hybrid BRKGA (with TS/GA metaheuristics mentioned)	14% reduction in cycle time; rapid convergence	Directly utilizes BRKGA in conveyor environments.
Fan & Su (2022)	Job Shop (JSSP)	CFT Conveyors (FIFO, finite buffers)	MILP & Simulated Annealing (SA-NGS)	Proved FIFO constraints limit the utility of increasing buffer size.	Direct match for CFT-JSSP constraints; lacks BRKGA-TS.
Voskresenskii et al. (2023)	Multi-Resource Project (RCPSP)	General industrial resource allocation	Hybrid GA + Tabu Search	38% improvement over standard GA via TS local intensification.	Validates the GA+TS synergy for complex makespan tasks.
Gheisariha et al. (2021)	Flexible Flow Shop (FFSSP)	Conveyor-based (Load/Unload/Travel)	Multi-objective Harmony Search (EMOHS)	Outperformed NSGA-II/MOPSO in sequence-dependent setup tasks.	Addresses conveyor logic in flow shop settings.
Fontes et al. (2023)	Job Shop (JSPT)	Automated Vehicles (Predetermined travel)	Hybrid PSO + Simulated Annealing	17–94% makespan improvement by coupling production and transport.	Focuses on vehicle-based transport rather than CFT.
(Costa, 2015)	Batch Flow Shop (FSMP)	Pharmaceutical internal loading	Hybrid GA with Focused Local Search	8.6% makespan reduction; high robustness in dynamic environments.	Relevant for hybrid GA logic and material limits.

Source: Author (2025)

The following discussion analyses these papers through the lenses of problem context and algorithmic architecture.

4.1.1. Problem Context: From General to Constrained Logistics

The research landscape reflects an increasing emphasis on integrating physical material handling constraints into the scheduling problem. While classical formulations often treat transportation as a secondary or negligible factor, the integration of Continuous Flow Transporters (CFT) necessitates a fundamental re-evaluation of system dynamics. Within this context, researchers such as Fan & Su (2022) have pioneered the integration of FIFO protocols and finite buffer capacities, demonstrating that these parameters create deterministic links between upstream entry and downstream processing that cannot be ignored.

This complexity is further amplified in flexible environments; for instance, Lopez-Juarez et al., (2024) contextualize the Flexible Job Shop (FJSSP) within highly automated robotic cells where conveyor belts act as the primary synchronization mechanism. Gheisariha et al., (2021) also addresses conveyor-based transportation but within a Flexible Flow Shop Scheduling Problem, which is structurally different from a job shop. Furthermore, the work of Fontes et al., (2023) emphasizes that coupling production with transportation, even in vehicle-based systems, results in profound makespan improvements, reinforcing the necessity of the hybrid metaheuristics in Job Shop Scheduling with Transport framework for modern industrial efficiency

4.1.2. Algorithmic Approach: Hybrid Metaheuristics

Parallel to the increasing complexity of manufacturing environments, algorithmic approaches have transitioned from monolithic metaheuristics toward sophisticated hybrid frameworks designed to balance the exploration-exploitation trade-off. A prominent trend is the hybridization of Genetic Algorithms (GA) with local search mechanisms to navigate the non-linear search spaces of constrained systems. The Biased Random-Key Genetic Algorithm (BRKGA) has emerged as a particularly robust tool for global exploration, as demonstrated by Lopez-Juarez et al. (2024), due to its ability to maintain solution feasibility through specialized decoders. However, to address the granular refinements required by limited buffers and blocking states, researchers frequently augment these global searches with intensive local exploitation.

The hybridization of Tabu Search (TS) with GA variants provides a critical precedent for current research; Voskresenskii et al., (2023) illustrate that memory-based local intensification can yield up to a 38% improvement in plan optimization compared to standalone evolutionary methods. Other high-impact strategies include the use of Simulated Annealing (SA) to manage the rigid FIFO constraints of CFT systems or the application of Particle Swarm Optimization (PSO) for vehicle coordination. Fontes et al. (2023) hybridize Particle Swarm Optimization (PSO) with SA to solve the JSPT, leveraging the strengths of both for complex transport resource allocation. Collectively, these studies suggest that the most effective architectures for solving the CFT-JSSP are those that successfully bridge the gap between stochastic global search and deterministic local refinement.

4.2. Synergy of BRKGA and Tabu Search

The hybridization of BRKGA and TS creates a dual-layer search mechanism that addresses the core weaknesses of each algorithm when used independently.

4.2.1. Exploration vs. Exploitation Dynamics

The Biased Random-Key Genetic Algorithm (BRKGA) functions as the primary mechanism for global exploration. By evolving a heterogeneous population of random-key vectors, the metaheuristic effectively samples expansive, non-contiguous regions within the search space. Nevertheless, the inherent stochasticity of genetic selection often precipitates a 'convergence bottleneck.' In this state, while the algorithm successfully identifies basins of high-quality solutions, its lack of local intensification results in a protracted search period to resolve the optimal local configuration within those regions.

Tabu Search (TS) mitigates these limitations by serving as the primary engine for local exploitation. When integrated into the BRKGA framework, TS is deployed specifically to the elite population to conduct an exhaustive search within their immediate basins of attraction. By employing memory-based mechanisms to proscribe recently visited states, the algorithm compels a systematic exploration of adjacent configurations, fine-grained perturbations that the stochastic crossover operator of the GA frequently bypasses. This ensures that the search does not merely identify high-potential regions but rigorously interrogates them to pinpoint the global optimum.

4.2.2. Integration Mechanisms

Three primary integration strategies were identified in the literature:

1. Sequential Integration: The BRKGA is run to convergence, and the best solution found is used as the initial seed for a deep Tabu Search (Ge et al., 2019).
2. Generational Local Search: In each generation, the Tabu Search is applied to a subset of the elite population to improve their fitness values before they are used for crossover (Barbosa & Melo, 2025; Song et al., 2025; Wang et al., 2025).
3. Memetic Approach: The Tabu Search is embedded directly into the mutation or crossover operators to ensure that all new offspring represent local optima in their respective neighborhoods (Luo et al., 2024).

4.3. Identified Research Gaps

While the constituent elements of this domain, namely job shop scheduling, conveyor-driven logistics, and metaheuristic optimization, are individually established within the literature, a critical research lacuna persists at their intersection. Specifically, the synergistic integration of a hybrid Biased Random-Key Genetic Algorithm (BRKGA) and Tabu Search (TS) remains under-explored in the context of JSSP formulations constrained by Continuous Flow Transport (CFT). This deficiency not only highlights the inherent originality of the current study but also presents a strategic opportunity to advance the theoretical frontier of logistical synchronization. By bridging these disparate domains, this research contributes a novel, high-resolution hybrid framework capable of navigating the combinatorial complexities of modern, integrated manufacturing and logistics ecosystems.

5. Final Consideration

This systematic literature review has provided an exhaustive examination of the intersection between hybrid metaheuristics and conveyor-constrained scheduling. The investigation confirms that the transition from traditional JSSP to CFT-JSSP introduces rigid synchronization constraints that necessitate a departure from simple sequence-based optimization toward integrated transport-production scheduling.

The primary conclusions of this study are as follows:

Hybridization Dominance: The combination of global evolutionary exploration (BRKGA) and intensive local search (TS) is fundamentally more capable of navigating the constrained solution spaces of CFT-JSSP than either algorithm in isolation.

Technological Maturation: Scientific production in this domain is showing exponential growth, driven by the global expansion of automated manufacturing.

Critical Need for CFT-Specific Decoders: The effectiveness of BRKGA hinges on the decoder's ability to translate random keys into feasible schedules. Future research must focus on developing decoders that inherently incorporate the FIFO rule and buffer capacities as fundamental constraints.

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