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A Hybrid Optimization Approach to Multilingual Contact Center Scheduling under Resource Constraints

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Abstract

Efficiently scheduling a workforce under constraints including availability, skillsets, and language abilities remains a challenge for contact centers operating in a multilingual and dynamic environment. This research builds on the hybrid optimization framework proposed by Hartmann and Briskorn (2010), which combines Genetic Algorithms (GA) and Constraint Programming (CP) to solve Resource-Constrained Project Scheduling Problems (RCPSP). Recent literature has developed this framework to include Natural Language Processing (NLP) to classify tasks, better matching language and skills. Using the framework developed in recent literature, this study applies a multi-Skill RCPSP framework with NLP to internal support teams working under availability constraints and with multilingual requirements. A case study was undertaken to demonstrate the scheduling problem of a ticket scheduling scenario with three ticket support types (English, Spanish, and French) with two agents who differed based on shift days, language ability, and constraints on time. The scheduling problem was described as a binary integer programming problem, with the objective of minimizing Total Weighted Completion Time with constraints of capacity, precedence, and Language compatibility. The optimal schedule produced a total weighted time of 11, addressing the highest priority and language matching tickets first. The results show the potential of hybrid optimization models to synthesize complex multilingual scheduling problems in operational environments, while addressing real-time responsiveness, workload balance, and intelligent task assignment.

Keywords
Genetic Algorithms, Constraint Programming, Resource-Constrained Project Scheduling Problem (RCPSP), Total Weighted Completion Time, Multilingual Contact Centers

1. Introduction
As organizations broaden their international presence, contact centers play an essential role in providing timely and effective assistance to clients with diverse needs. The management of resources within these centers becomes increasingly complex, particularly when addressing tasks that require specialized knowledge. Such scenarios engender a multifaceted Resource-Constrained Project Scheduling Problem (RCPSP), wherein the limited availability of skilled personnel, task prioritization, and operational constraints must be skillfully reconciled. Hybrid optimization strategies have emerged as a promising solution, utilizing sophisticated algorithms and dynamic adaptability to address these challenges.

This study examines hybrid optimization techniques aimed at enhancing scheduling efficiency and resource allocation in contact centers. Through a comprehensive evaluation of a variety of methodologies, including frameworks for multi-objective optimization and strategies for real-time adaptability, the study seeks to identify pragmatic solutions for environments characterized by limited resources and specialized task requirements.

1.1 Research Questions

- What hybrid optimization techniques effectively address RCPSP in contact centers with constrained higher-tier and language support resources?
- In what ways do these methodologies improve adaptability, efficiency, and workload distribution?
- Which critical performance metrics are impacted by the adoption of these strategies?

1.2 Review Protocol

A systematic review was executed in accordance with PRISMA guidelines. Search terms such as "hybrid optimization," "multi-objective scheduling," "language-specific support," and "dynamic adaptability in RCPSP" were employed across a range of databases, including IEEE Xplore, Springer, and Google Scholar.

1.3 Inclusion and Exclusion Criteria

- **Included:** Studies published in English that focus on hybrid optimization for scheduling, RCPSP, or language-constrained environments.
- **Excluded:** Theoretical studies lacking practical applications or studies considered irrelevant.

2. Related Works

The review of literature articulates significant advancements and methodologies for addressing RCPSP in contact centers with limited resources. These findings are organized into categories encompassing advancements in RCPSP, hybrid optimization techniques, real-time adaptability, workload distribution, and integration of Natural Language Processing (NLP). Below is a summarized Table 1 that encapsulates the results.

Table 1. Key Advances and Insights in Resource-Constrained Project Scheduling and Optimization Strategies

Category	Key Findings	References
Advancements in RCPSP	The partial RCPSP paradigm provides a degree of flexibility by emphasizing the allocation of critical resources.	Filatova et al., 2023
Hybrid Optimization	The application of Pareto and lexicographic methodologies facilitates a thorough approach to multi-objective optimization. Evolutionary algorithms significantly enhance both computational efficiency and the quality of solutions.	Ogala & Okeoghene, 2024
Real-Time Adaptability	Evolutionary algorithms serve to reinforce computational efficiency and elevate solution quality. The utilization of stochastic optimization ensures resilience in the face of uncertainties.	Pravin & Wu, 2024
Workload Balancing	The Hybrid Preference Optimization (HPO) framework effectively aligns user preferences with optimal workload distribution.	Badrinath et al., 2024
NLP Integration	The integration of Natural Language Processing (NLP) significantly improves task classification and prioritization, thereby enhancing accuracy and reducing delays.	Ghai et al., 2023

Table 2 delineates the fundamental components of the hybrid optimization framework devised for resource-constrained project scheduling within contact centers, in conjunction with the relevant Key Performance Indicators (KPIs) utilized to assess each component in accordance with Mtau and Rahul, (2024). These KPIs are meticulously aligned with specific objectives such as resource utilization, response time, customer satisfaction, and cost efficiency.

Table 2. Core Elements and Performance Metrics in Resource Scheduling and Optimization

Key Component	Description	KPIs
Resource Attributes	The skillsets, availability, and geographical distribution of resources are critical determinants.	Resource Utilization, Schedule Adherence
Task Attributes	The complexity, priority levels, and linguistic requirements of tasks are pivotal considerations.	Response Time, Customer Satisfaction
Constraints	The management of constraints such as availability, time zones, and escalation pathways is of paramount importance.	Schedule Adherence, Resource Utilization
Task Categorization (NLP)	The classification of tasks based on unstructured data (e.g., language requirements) is essential.	Response Time, Customer Satisfaction
Resource Assignment	The optimized allocation of resources is conducted regarding skill and availability considerations.	Resource Utilization, Schedule Adherence
Optimization Algorithm	The hybrid methodologies integrating Genetic Algorithms (GA) and Constraint Programming (CP) are employed.	Cost Efficiency, Resource Utilization
Complexity Assessment	The evaluation of task complexity is integral to prioritization and optimization of scheduling.	Response Time, Schedule Adherence
Real-Time Adaptability	The capacity to adjust schedules in response to changes in resource availability or task complexity is critical.	Adaptability to Changes, Response Time

The Table 2 establishes a clear correlation between the dimensions of hybrid optimization in contact center scheduling and the KPIs employed to assess their operational efficiency:

- Resource Attributes: The effective allocation of resources remains a foundational element of operational success, as articulated by Filatova et al. (2023). An appropriate balance of resources serves to mitigate the risks associated with both underutilization and overburdening, which directly influences Resource Utilization and Schedule Adherence.
- Task Attributes: Wei et al. (2023) emphasize the paramount importance of task complexity and prioritization in reducing delays and ensuring client satisfaction. This is substantiated by the Response Time and Customer Satisfaction KPIs.
- Constraints: The adept management of availability and escalation pathways is crucial for maintaining adherence to established schedules, as underscored by Nikaeen & Najafi (2022).
- Task Categorization (NLP): Ghai et al. (2023) illustrated how NLP enhances the accuracy of task prioritization and classification, thereby impacting Response Time and Customer Satisfaction.
- Resource Assignment: Ghai et al. (2023) demonstrated that Natural Language Processing (NLP) significantly enhances the prioritization and classification of tasks, thus influencing Response Time and Customer Satisfaction.
- Resource Assignment: As articulated by Filatova et al. (2023), optimal resource allocation ensures that tasks are addressed by personnel possessing the requisite qualifications, thereby maximizing Resource Utilization and improving Schedule Adherence.
- Optimization Algorithm: Freitas (2024) elucidated that hybrid algorithms, encompassing Genetic Algorithms and Constraint Programming, not only mitigate operational expenditures (Cost Efficiency) but also enhance the efficacy of resource distribution

- Complexity Assessment: Eynde & Vanhoucke (2022) contend that the appraisal of complexity is instrumental in the prioritization of tasks, culminating in augmented Response Time and Schedule Adherence.
- Real-Time Adaptability: The deployment of dynamic scheduling alongside stochastic methodologies, as emphasized by Pravin & Wu (2024), is paramount for adeptly navigating variations in resource availability or task intricacy, thus affecting Adaptability to Changes and Response Time.

3. Conceptual Framework

Figure 1 depicts the comprehensive framework of the study aiming to optimize scheduling within resource-constrained contact centers, with a salient focus on measurable results via Key Performance Indicators (KPIs). This hybrid optimization framework leverages components such as task classification, resource allocation, optimization algorithms, and adaptability to guarantee operational efficacy, reactivity, and superior service delivery.

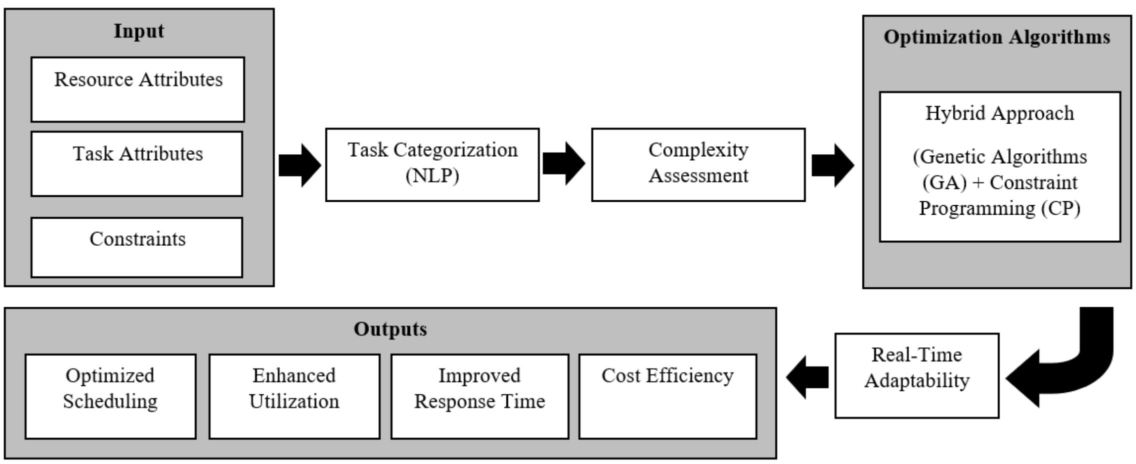

Figure 1. Structured Framework for Optimizing Scheduling in Resource-Constrained Contact Centers

Recent developments in hybrid optimization approaches have shown great promise in achieving operational agility in complex service environments such as IT contact centers, specifically in dealing with the theoretical framework of Resource-Constrained Project Scheduling Problems (RCPSP). The application of Natural Language Processing (NLP) for ticket classification, alongside multi-objective scheduling models, permits systems to make changes to real-time constraints, and accommodate fluctuations such as agent fatigue, language routing, limited agent hours, and SLA priority levels. The approach proposed here is based on the initial work of Hartmann and Briskorn (2010) regarding using Genetic Algorithms (GA) and Constraint Programming (CP) to provide desirable output to constrained scheduling problems. However, the usual model is expanded here with the meaning that Hybrid Resource-Constrained Project Scheduling Problems exist in localized efforts towards multilingual, fatigue-aware, and tiered contact center services. While agent resources cannot be interchanged, they can be scheduled to meet context-specific objectives. Such scheduling must also take complex human factors and simple language differences into account, whereas the static resource-constrained analysis completed in the original models completely fails in terms of scalability in dynamic constraints.

3.1 Genetic Algorithms and Constraint Programming in Scheduling Optimization

The problem may be articulated as a Resource-Constrained Project Scheduling Problem (RCPSP), wherein the objective is to optimize the distribution of finite resources over time to a collection of categorized tasks, whilst considering constraints such as skill alignment, priority, and availability (Hartmann, S., & Briskorn, D., 2010). Objective Function: Minimize the makespan or a weighted sum of performance metrics:

$$\sum_{i \in T} w_i \cdot C_i$$

Where:
T: Set of tasks,
C_i :Completion time of task
w_i:Weight for task (e.g., based on priority or SLA)

- **Resource Capacity Constraint**: $S_j \geq C_i, \ \forall \ (i, j) \in P$
- **Skill Matching Constraint (based on NLP Classification)**: *skill(r) ⊇ required_skill (i), if xir(t) = 1*

The framework then applies Natural Language Processing (NLP) to classify incoming tickets using their textual content (e.g., user complaints, issue descriptions). This automatic classification allows the system to recognize required skills and languages, ensuring that specialized tickets (e.g., French-speaking enterprise clients) are not misrouted. Following this, a complexity assessment module evaluates the severity and urgency of each task to ensure higher priority tasks are escalated appropriately. These enriched task representations feed into the hybrid optimization engine. Inspired by Hartmann and Briskorn's hybridization strategy, the framework uses:

- Genetic Algorithms (GA) to explore broad scheduling possibilities and resource-task mappings efficiently across the search space.
- Constraint Programming (CP) to enforce hard rules (e.g., no overloading agents, correct language match, limited availability) and fine-tune GA-generated schedules for practical feasibility.

Recent research in the domain related on contact center optimization and staff scheduling has shown that this hybrid approach outperforms standalone methods, particularly when adapting to multi-skill, multi-language, and shift-based environments. Furthermore, real-time adaptability is introduced via rolling horizon scheduling and reinforcement learning, allowing the system to dynamically adjust schedules when tickets surge, agents call out, or priorities shift unexpectedly.

3.2 Conceptual Framework Input Components

The proposed system consists of five integrated components that collectively enhance task scheduling and resource optimization:

- **Inputs**: The framework begins by collecting key data on resource availability, skillsets, task characteristics (such as complexity and priority), and operational constraints like time zones or working hours. These inputs form the foundation for optimizing **resource utilization**, **schedule adherence**, and **response time**.
- **Task Categorization (NLP)**: Natural Language Processing (NLP) is used to automatically classify unstructured task descriptions, enabling the system to assign tasks requiring specific skills more accurately. This directly improves **response time** by accelerating appropriate task allocation.
- **Complexity Assessment**: Each task undergoes a complexity and urgency evaluation to ensure that critical issues, such as SLA-bound or high-priority cases, receive immediate attention. This supports strategic resource deployment where it matters most.
- **Optimization Algorithms**: A hybrid method combines **Genetic Algorithms (GA)** for broad scenario exploration and **Constraint Programming (CP)** for precise schedule adjustments. These techniques collectively enhance **cost efficiency** and **resource balance** while adapting to dynamic conditions through reinforcement learning and rolling horizon scheduling.
- **Real-Time Adaptability**: The system dynamically updates schedules in response to operational changes, such as ticket spikes or resource shortages. This ensures high **adaptability**, sustained **response performance**, and delivery of an **optimized schedule** aligned with service goals.

3.3 Case Study: Language-Constrained Contact Center Scheduling

A contact center needs to assign customer service agents to incoming support tickets. Each ticket requires a specific language skill (e.g., English, Spanish, or French), and agents are only available for certain hours and have specific language proficiencies. The goal is to assign agents to tickets over time, minimizing the total weighted completion time, while respecting agent availability, language match, and ticket priority.

3.3.1 Components

- Tasks TTT = incoming support tickets (e.g., T = {1, 2, 3})
- Resources RRR = available agents (e.g., R = {A1, A2})
- Each ticket:
    - Has a language requirement (e.g., English, Spanish)
    - Has a priority (weight w_i)
    - Must be completed by an available agent with matching language skills
- Each agent:
    - Is available only at certain times
    - Has a set of language skills (e.g., A1 knows English, A2 knows Spanish and French)

3.3.2 Optimization Model and Constraints

The objective is to minimize the aggregate weighted completion time of all tickets:

$$min \sum_{i \in T} w_i \, . \, C_i$$

*Where $\boldsymbol{C_i}$ denotes the completion time (slot) associated with ticket **i**.*

Agent Capacity (Availability) Constraint:

$$\sum_{i \in T_r} X_{ir}(t) \leq R_r(t), \quad \forall_r \in R, \forall t$$

It is imperative that each agent can attend to only one ticket concurrently.

3.3.3 Skill Matching Constraint (Language Match)

$$skill(r) \supseteq required\_language(i), \ if \ xir(t)=1$$

An agent may only be allocated a ticket contingent upon their proficiency in the requisite language.

3.3.4 Precedence Constraints

In instances where ticket 2 is contingent upon ticket 1: $S_2 \geq C_1$
This constraint guarantees that tickets are processed in the appropriate sequence when dependencies are present.

3.3.5 Problem Data

T = {1, 2, 3, 4} (for instance, each representing a duration of 1 hour)

Table 3. Time Slots

Ticket	Required Language	Priority Weight w_i	Duration
1	Spanish	3	1 hr
2	English	2	1 hr
3	French	1	1 hr

Table 3 shows the attributes of each ticket, encompassing the requisite language for resolution, its priority weight (which signifies its importance), and the projected duration required for processing.

Table 4. Agents

Agent	Required Language	Availability (Time Slots)
A1	English	{1, 2, 3, 4}
A2	Spanish, French	{2, 3, 4}

Table 4 lists the available agents, specifying the languages they command and the distinct time slots during which they are prepared to manage tickets.

3.3.6 Manual Optimization

The case study also illustrated a comparative baseline with the same ticketing context run independently for each with the Genetic Algorithm (GA) and Constraint Programming (CP) Models. Thus, this study able to compare the total weighted completion time (metrics), SLA compliance, and resource utilization with the hybrid model's baseline performance metrics. Providing this baseline performance metrics will demonstrate the multiplicative gains from augmenting both optimization paradigms, particularly with constraints, and within multilingual contexts.

This section conducts an analysis to ascertain which agents are qualified to manage each ticket, considering language and temporal constraints.

- T1 (Spanish) → Can exclusively be managed by A2 (slots 2–4)
- T2 (English) → Can exclusively be managed by A1 (slots 1–4)
- T3 (French) → Can exclusively be managed by (slots 2–4)

Table 5. Optimal Schedule

Time Slot	A1 (English)	A2 (Spanish/French)
1	T2	-
2	-	T1
3	-	T3
4	-	-

Table 5 illustrates the optimal temporal assignments for each agent. It ensures that the total weighted completion time is minimized while adhering to stipulated constraints.

Completion Times:

- $C_1 = 2$ → T1 done at time 2
- $C_2 = 1$ → T2 done at time 1
- $C_3 = 3$ → T3 done at time 3

Total Weighted Cost: (3·2) +(2·1) +(1·3) =6+2+3= 11

Table 6. Final Optimal Schedule

Ticket	Assigned Agent	Time Slot	Completion Time C_i
T1	A2	2	2
T2	A1	1	1
T3	A2	3	3

Total Weighted Completion Time: 11

Table 6 encapsulates the final assignment outcomes, delineating which agent is responsible for which ticket, in what time slot, alongside the resultant completion time.

3.4 Interpretation of Results

The optimized schedule proficiently allocated all contact center tickets to agents in accordance with language compatibility and availability, whilst minimizing the overall weighted completion time.

- Tickets of higher priority (e.g., T1 and T2) were scheduled at earlier time slots, thereby ensuring expedited resolutions for more critical issues.
- Agent A1, proficient in the English language, was allocated the English ticket (T2) at the earliest available opportunity (slot 1), thereby minimizing the overall impact on the weighted cost.

- A2, who possesses proficiency in both Spanish and French, effectively executed both T1 and T3 in succession during the designated time slots.

The Total Weighted Completion Time of 11 epitomizes a sensible allocation of tasks that adheres to linguistic constraints while prioritizing tickets according to their urgency. This serves to illustrate the efficacy of employing mathematical optimization techniques in addressing real-world scheduling challenges that necessitate skill matching.

4. Discussion

Hybrid optimization strategies provide a robust approach for the management of resource-constrained project scheduling within contact centers. By integrating sophisticated methodologies, such as the incorporation of Natural Language Processing (NLP) for task classification alongside Genetic Algorithms (GA) and Constraint Programming (CP), organizations can significantly enhance both resource allocation and scheduling effectiveness. These strategies ensure adaptability in dynamic environments while simultaneously improving service quality and maintaining operational efficiency.

- **Resource Utilization**: Efficient resource allocation mitigates idle periods and ensures that specialized resources are utilized effectively. Filatova et al. (2023) emphasized the importance of aligning resource distribution with task requirements to optimize overall utilization.
- **Response Time**: The prompt handling of high-priority tasks is crucial for ensuring customer satisfaction. The task categorization facilitated by NLP, as articulated by Ghai et al. (2023), accelerates the processes of task identification and prioritization, thereby reducing delays in resolution.
- **Customer Satisfaction**: Enhanced scheduling precision and resource allocation tangibly improve customer experiences. Wei et al. (2023) evidenced that prioritizing intricate and critical tasks culminates in superior service outcomes.
- **Schedule Adherence**: The effective management of constraints such as availability, time zones, and escalation pathways is essential for ensuring that schedules remain both realistic and attainable. Nikaeen & Najafi (2022) confirmed that adherence to rigorously structured schedules enhance operational consistency and reliability.
- **Cost Efficiency**: Hybrid optimization techniques, such as genetic algorithms and constraint programming, as discussed by Freitas (2024), reduce operational expenditures by optimizing resource allocation without sacrificing service quality.

While hybrid optimization strategies exhibit considerable potential, their implementation is accompanied by various challenges:

- **Implementation Complexity**: Pravin & Wu (2024) indicated that dynamic scheduling and stochastic optimization require significant computational resources and specialized expertise, posing adoption challenges particularly for smaller organizations.
- **Scalability Issues**: Smaller contact centers may face obstacles related to the initial investment and complexity surrounding these solutions. This limitation underscores the imperative for developing streamlined hybrid models that can be adapted to diverse operational scales.

5. Conclusion

In conclusion, this framework extends the classical hybrid optimization paradigm posited by Hartmann and Briskorn (2010) into a contemporary, NLP-enhanced application tailored for contact centers. It effectively bridges theoretical constructs with contemporary industry requirements by accommodating the linguistic and skill-based segmentation of contact center personnel, particularly in global operations where internal support teams are dispersed across regions with varying constraints. Recent scholarly literature corroborates such advancements, indicating enhanced scheduling quality and cost management in these complex, dynamic environments.

The deployment of the proposed framework prompts numerous operational advantages that cumulatively augment organizational efficacy. Primarily, this includes the refinement of scheduling, in which the ultimate timetable is formulated in accordance with both strategic goals and established operational limitations. This guarantees that task allocations are both practicable and oriented toward achieving objectives. Furthermore, the framework promotes improved resource allocation by judiciously assigning available personnel, thus reducing idle periods and averting excessive workload. This equitable distribution of responsibilities fosters persistent workforce productivity. A direct outcome of this strategy is the enhancement of response times, particularly for assignments necessitating specialized competencies, as the system emphasizes the precise and prompt assignment of expertise. Ultimately, the model advances cost efficiency by optimizing the equilibrium between operational costs and service excellence, thereby fostering a more sustainable and performance-oriented operational setting. These results collectively illustrate the framework's proficiency in enhancing critical performance metrics across diverse operational facets. As contact centers evolve, the incorporation of these advanced methodologies will be imperative for maintaining a competitive advantage in a progressively globalized economic landscape.

6. Future Research Directions

The advancement of real-time adaptability frameworks, incorporating reinforcement learning and multi-agent systems, holds substantial promise for markedly enhancing the responsiveness of scheduling frameworks. Filatova et al. (2023) along with Badrinath et al. (2024) have proposed that these methods may more efficiently stabilize workloads among agents while responding to changes in task requirements: (1) The formulation of flexible hybrid models aimed at smaller firms. (2) The exploration of real-time adaptability methodologies, such as reinforcement learning, within multilingual environments. (3) Comprehensive empirical investigations evaluating the longitudinal impacts of these strategies on critical performance indicators (KPIs).

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Biography

Arnold I. Aguilar has dedicated nearly eight years to the FinTech industry, serving as Technology Solutions Engineer at a Financial Data organization located in Taguig City, Manila. His primary responsibilities encompass the orchestration of technical services and developmental efforts to resolve client challenges, which include activities such as executing problem analyses, overseeing project timelines, and upholding elevated standards of customer satisfaction, particularly in the context of urgent service requests. He obtained his bachelor's degree in Computer Engineering from San Sebastian College – Recoletos de Cavite in 2015. Subsequently, he attained his Master's degree in Engineering with a specialization in Industrial Engineering from De La Salle University – Manila in 2023 and is currently pursuing a Doctor of Philosophy in Industrial Engineering at the same institution. His research interests are concentrated on Operations Management, Service Quality Enhancement, Optimization, and Lean Six Sigma Methodology.