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Analyzing Bounded Hub-Spoke Allocation in Single Allocation Hub Location Problem

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ABSTRACT

The hub location problem (HLP) is widely used to design hub-and-spoke networks by consolidating flows through selected hub facilities. However, standard formulations may produce solutions in which some hubs are connected to very few spokes, while others serve a disproportionately large number of spokes, resulting in inefficient hub utilization. This study aims to investigate the impact of imposing explicit lower bound and combined lower and upper bounds on hub–spoke allocations to improve hub utilization. The contribution of this study is to introduce two bounded spoke allocation constraints and systematically evaluating their impact on computational performance, total cost, network structure, and hub location decisions. A flow-based single allocation hub location formulation is adopted, and computational experiments are conducted on the CAB and TN benchmark datasets under various parameter settings. The results show that the lower bound eliminates hubs with very few spokes, while the upper bound limits excessive concentration of spokes, leading to more controlled hub and spoke configurations. The proposed constraints may also alter hub location decisions. The impact on total cost is small, with average increases of about 1.23% and 0.99% for the lower bound model, and 1.38% and 1.52% for the combined lower and upper bounds model in the CAB and TN datasets, respectively. Although computational effort increases for larger instances, the proposed approach provides decision-makers with a practical mechanism for controlling hub utilization.

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1. Introduction

The hub location problem commonly arises in the design and planning of transportation and telecommunication networks. In transportation, its applications include express parcel and postal services, containerized shipping, energy distribution, trucking, air cargo transport, passenger mobility, and rapid transit systems, while in telecommunications it is relevant to the development of distributed data networks composed of facilities such as switches, concentrators, multiplexers, and routers (Alumur et al., 2021; Contreras, 2021; Contreras & O'Kelly, 2019; Setiawan et al., 2025a, 2025b). A key feature of hub location systems is the use of hub facilities as consolidation, break-bulk, and transshipment points for routing flows from origin (supply) nodes to destination (demand) nodes. In particular, hubs separate flows from a common origin destined for different endpoints, while simultaneously consolidating flows from multiple origins that share the same destination.

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The hub location problem is based on a hub-and-spoke network structure, where hub nodes act as consolidation points and the remaining nodes are assigned to the selected hubs as spokes. The network consists of access links connecting spokes to hubs and inter-hub links connecting hubs to one another. This structure provides several benefits, including reduced transportation costs through economies of scale, lower infrastructure investment due to a sparser network design, and improved service levels via more frequent connections (Alumur et al., 2021; Harits et al., 2025).

The hub location problem (HLP) involves determining the optimal placement of hub facilities, assigning the remaining nodes to these hubs, designing both the access and inter-hub networks, and routing flows through the network so as to minimize total cost. The problem was originally introduced in the pioneering studies of O'kelly (1987) as the p-HLP, where the number of hubs to be established is fixed at p. Since then, an extensive body of literature has emerged (see, for example (Alumur et al., 2012, 2021; Alumur & Kara, 2008; Basallo-Triana et al., 2023; Campbell & O'Kelly, 2012; Cobeña et al., 2023; Contreras, 2021; Contreras & O'Kelly, 2019; Espejo et al., 2023, 2025; Farahani et al., 2013; Ghaffarinasab et al., 2022; Ghaffarinasab & Kara, 2019; Meier & Clausen, 2018; O'Kelly et al., 2025; Oliveira et al., 2022; Shah et al., 2025; Wandelt et al., 2021, 2022), encompassing a wide range of extensions and applications, including intermodal transportation systems (Basallo-Triana et al., 2021). Various alternative formulations have been proposed, with a comprehensive review provided by (Setiawan et al., 2025a). Existing studies primarily focus on hub selection and transportation cost minimization, whereas explicit control over the number of spokes assigned to each hub has received comparatively less attention.

Consequently, the resulting solutions may contain hubs connected to only one spoke node or even to none in certain instances. Such outcomes are undesirable because they undermine the fundamental role of hubs as consolidation points for flows from multiple origins, thereby limiting the intended benefits of flow aggregation (Alumur et al., 2021; Contreras, 2021; Contreras & O'Kelly, 2019; Li et al., 2025). On the other hand, without an upper bound, a large number of spokes may be assigned to a small number of hubs, leading to overly centralized network structures. In such cases, a small number of hubs dominate the network, potentially causing congestion, operational inefficiencies, and reduced service quality. Moreover, in practical applications, hub facilities often face limitations in handling connections due to infrastructure, workforce, or scheduling constraints. Therefore, explicitly regulating the number of spokes assigned to each hub is expected to produce hub–and–spoke networks that better reflect both consolidation requirements and practical operational considerations.

This paper considers the single allocation hub location (Alumur et al., 2009, 2016; Contreras et al., 2017; Dukkanci et al., 2019; Serper & Alumur, 2016; Taherkhani & Alumur, 2019), in which each spoke (non-hub) node is assigned to exactly one hub. Fig. 1 illustrates a single allocation hub location problem where the squares numbered 1, 2 and 3 are hubs and the circles numbered 4-9 are the spokes (non-hub) nodes. Fig. 1 shows that each hub has two spokes assigned to them.

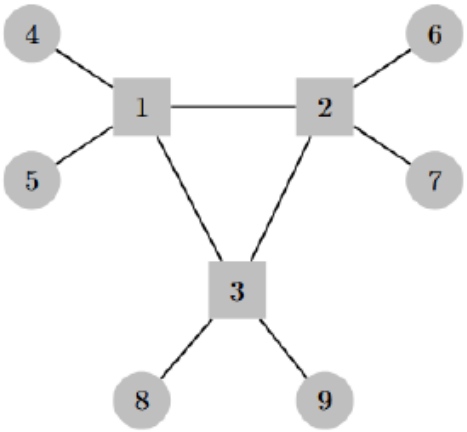


Fig. 1. Single allocation hub location problem

Motivated by these observations, this paper investigates the use of explicit bounds on hub–spoke allocations. The contribution of this study is twofold. First, we investigate two bounded hub–spoke allocation settings by incorporating lower-bound and combined lower-and-upper-bound constraints into the single allocation hub location problem. Second, we analyze the impact of these constraints on total cost, computational time, hub location, and spoke distribution, providing managerial insights into the trade-off between efficiency and structural control in hub-and-spoke network design.

2. Method

This section presents the modeling framework for the single-allocation hub location problem with bounded hub–spoke assignments. After introducing the basic model and notation, two variants are considered: one with a lower bound on spokes per hub and another with both lower and upper bounds, to assess their impact on solution time, cost, and network structure.

2.1. Basic Single Allocation Hub Location Problem Formulation

Several formulations exist for the basic single allocation hub location problem (Setiawan et al., 2025a). In this study, we adopt the flow-based formulation proposed by Ernst & Krishnamoorthy (1996), as it has been shown to provide shorter solution times when solved using commercial solvers (Setiawan et al., 2025b). This choice is particularly suitable for the purpose of this paper, which focuses on analyzing the effects of imposing lower bounds and combined lower and upper bounds on hub–spoke allocations. In addition, this formulation has been used to model many extensions of single allocation HLP (Alumur et al., 2009, 2016; Dukkanci et al., 2019; Serper & Alumur, 2016).

For each node pair $i, j \in N$, the parameter w_{ij} denotes the amount of demand to be routed from node i to j and the parameter c_{ij} denotes transportation cost of a unit of flow between node i to j. Parameter α $(0 < \alpha < 1)$ used as a discount factor to provide reduced unit flow costs on transport between hubs to reflect economies of scale resulting from consolidation of flows between hubs and parameter p is the number of hubs to be established. Let $O_i = \sum_{j \in N} w_{ij}$ denote the total outbound flow from node i and $D_i = \sum_{j \in N} w_{ji}$ denote the total inbound flow to node i. The flow-based formulation uses a binary allocation variable z_{ik} which is equal to one if node $i \in N$ is assigned to hub $k \in N$, and 0 otherwise. In particular, a node $k \in N$ allocated to itself ($z_{kk} = 1$) implies that node k is selected as a hub. In addition to z_{ik} variables, this formulation uses a non-negative y_{ikm} to reflect the amount of flow originating at node i and passing through hubs k and m. The flow-based formulation of the single allocation hub location problem is presented below in Eq. (1), Eq. (2), Eq. (3), Eq. (4), Eq. (5), Eq. (6), Eq. (7).

$$Min \sum_{i \in N} \sum_{k \in N} c_{ik} z_{ik} (O_i + D_i) + \sum_{i \in N} \sum_{k \in N} \sum_{m \in N} \alpha \, c_{km} \, y_{ikm} \tag{1}$$

$$\sum_{k \in N} z_{kk} = p \tag{2}$$

$$\sum_{k \in N} z_{ik} = 1 \qquad \forall i \in N \tag{3}$$

$$z_{ik} \leq z_{kk} \qquad \forall i, k \in N \tag{4}$$

$$\sum_{m \in N} y_{ikm} - \sum_{m \in N} y_{imk} = O_i z_{ik} - \sum_{j \in N} w_{ij} z_{jk} \qquad \forall i, k \in N \tag{5}$$

$$z_{ik} \in \{0,1\} \qquad \forall i, k \in N \tag{6}$$

$$y_{ikm} \geq 0 \qquad \forall i, k, m \in N \tag{7}$$

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2.2. Lower Bound on Spoke Allocation

Eq. (1) minimizes the cost of flow where the first and second components model the flow cost on access edges and hub edges, respectively. Eq. (2) ensures that exactly p hubs are open. Eq. (3) enforces each node to be allocated only to one hub. Eq. (4) ensures that if a node i is allocated to node k, then node k should be a hub. Eq. (5) states that the flow entering to hub k either directly from node i or via other hubs m has to be equal to the flow leaving to either other hubs m or to destination nodes j. Finally, Eq. (6) and Eq. (7) impose the integrality and non-negativity restrictions, respectively.

2.3. Lower Bound on Spoke Allocation

To prevent the occurrence of underutilized hubs, a lower bound on the number of spokes assigned to each hub is introduced. Specifically, each hub is required to serve at least a predefined number of spokes. The lower bound constraint is formulated as follows, where L denotes the minimum number of spokes assigned to each hub. Eq. (8) imposes a minimum number of spokes for every selected hub, ensuring that each hub functions as an effective consolidation point. To ensure feasibility, the value of L should be selected such that the total number of non-hub nodes is sufficient to satisfy the minimum spoke requirement for all hubs.

$$\sum_{i \in N, i \neq k} z_{ik} \geq L\, z_{kk} \qquad \forall k \in N \tag{8}$$

2.4. Lower and Upper Bounds on Spoke Allocation

In addition to the lower bound, an upper bound is introduced to prevent excessive concentration of spokes on a single hub. This reflects practical limitations in handling connections and avoids overly centralized network structures. The upper-bound constraint in Eq. (9) is formulated as follows, where U represents the maximum number of spokes assigned to each hub. Similarly, the upper bound parameter U should be chosen appropriately to allow feasible spoke assignments.

$$\sum_{i \in N, i \neq k} z_{ik} \leq U\, z_{kk} \qquad \forall k \in N \tag{9}$$

Together with the Eq. (8) presented in Section 2.2, this formulation ensures that each hub serves a bounded number of spokes.

2.5. Benchmark datasets and parameter settings

The proposed models are evaluated using the CAB and TN benchmark datasets, which are widely used in the hub location literature (Alumur et al., 2021; Contreras & O'Kelly, 2019; Setiawan et al., 2025a, 2025b). The CAB dataset represents small to medium sized instances, whereas the TN dataset contains larger and more computationally challenging instances. The values of L and U were selected to represent different levels of hub utilization while satisfying the feasibility conditions of the proposed formulations. Multiple combinations of L and U were evaluated to assess their effects on the objective function, computational time, network structure, and hub location decisions.

3. Results and Discussion

This section reports the datasets, experimental settings, and computational results of the proposed models. The findings are analyzed in terms of computational performance, total cost, and network structure, and are further discussed to derive managerial insights.

3.1. Datasets and Experimental Setting

The computational experiments are conducted using two widely adopted benchmark datasets in the HLP literature, namely the CAB (Civil Aviation Board) and TN (Turkish Network) datasets. For the CAB dataset, all 25 nodes are considered with p = 4,6,8. For the TN dataset, subsets of 40 and 50 nodes are used, with $p \in \{6,8,10\}$. For all combinations of node sizes and hub numbers, the discount factor is set to $\alpha \in \{0.2,0.4,0.6,0.8\}$. The experiments are performed on an ASUS VivoBook X403FA_K403FA equipped with an Intel i3-8145U CPU (2.1 GHz) and 4 GB of RAM, running

Windows. The models are implemented in JuMP, an open-source algebraic modeling language embedded in the Julia environment, and solved using IBM ILOG CPLEX version 12.10 with default parameter settings. Each instance is solved with a time limit of 3.600 seconds (1 hour).

3.2. Computational Experiment and Results

This section presents the computational experiments and discusses the results in terms of computational time, total cost, and network structure, focusing on the impact of the proposed spoke allocation constraints.

3.2.1. Computational Time

This section analyses the computational impact of introducing lower bound constraints and combined lower and upper bound constraints on spoke allocation in the single allocation hub location problem. The computational times obtained for the CAB and TN datasets are reported in Table 1 and Table 2, respectively.

Table 1. Computational time for CAB

N	p	α	L	U	Computational Time		
					Basic	With L	With L and U
25	4	0.8	3	6	9.94	9.15	7.91
		0.6	3	6	3.71	3.84	4.51
		0.4	3	6	2.42	2.92	1.10
		0.2	3	6	0.55	0.73	0.72
25	6	0.8	2	5	24.92	10.17	7.86
		0.6	2	5	9.63	9.51	4.69
		0.4	2	5	3.28	4.52	1.89
		0.2	2	5	0.81	1.01	0.89
25	6	0.8	3	5	24.92	6.06	6.47
		0.6	3	5	9.63	2.77	2.98
		0.4	3	5	3.28	1.10	1.02
		0.2	3	5	0.81	0.65	0.57
25	8	0.8	2	5	25.86	11.35	11.65
		0.6	2	5	8.35	6.68	5.30
		0.4	2	5	3.03	3.99	3.58
		0.2	2	5	0.91	2.57	1.88

The computational results reveal that the impact of the proposed constraints on solution time is not uniform across all instances. For the CAB dataset, which represents relatively smaller problem sizes, the introduction of lower bound constraints and combined lower and upper bounds often reduces computational time compared to the basic model. In contrast, for the larger TN dataset, the additional constraints generally increase computational time, with several large instances reaching the prescribed time limit (TILIM).

This difference can be explained by the interaction between problem size and the feasible solution space. For the CAB dataset, the additional constraints reduce the feasible solution space, which appears to help the solver identify optimal solutions more efficiently. However, for the TN dataset, the much larger number of nodes and allocation decisions results in a substantially more difficult optimization problem. Although the feasible solution space is also reduced, the added structural constraints increase the overall complexity of the search process, leading to greater computational effort and longer solution times. The computational impact also depends on the parameter settings. In general, tighter spoke allocation requirements, particularly larger lower bounds or the simultaneous use of lower and upper bounds, further restrict the feasible solution space. While this additional restriction may simplify some small instances, it generally increases computational effort for larger instances, several of which cannot be solved to optimality within the specified time limit.

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Table 2. Computational time for TN

N	p	α	L	U	Computational Time		
					Basic	With L	With L and U
40	6	0.8	4	8	46.97	67.66	59.92
		0.6	4	8	37.43	50.23	65.94
		0.4	4	8	10.02	17.26	23.38
		0.2	4	8	4.15	11.61	9.25
40	6	0.8	3	7	46.97	109.56	115.48
		0.6	3	7	37.43	46.35	53.66
		0.4	3	7	10.02	12.33	70.07
		0.2	3	7	4.15	4.57	12.39
40	8	0.8	3	6	34.71	60.55	58.10
		0.6	3	6	41.57	27.01	44.59
		0.4	3	6	7.76	8.20	6.86
		0.2	3	6	3.03	3.46	2.49
40	8	0.8	2	5	34.71	45.65	70.05
		0.6	2	5	41.57	29.35	100.68
		0.4	2	5	7.76	6.69	54.00
		0.2	2	5	3.03	2.49	6.16
50	8	0.8	5	7	748.47	1001.73	1155.83
		0.6	5	7	177.02	294.52	354.84
		0.4	5	7	87.24	125.54	101.36
		0.2	5	7	12.52	17.07	25.61
50	8	0.8	4	7	748.47	TILIM	TILIM
		0.6	4	7	177.02	402.16	386.96
		0.4	4	7	87.24	115.23	88.28
		0.2	4	7	12.52	15.12	13.83
50	8	0.8	3	6	748.47	750.78	2005.51
		0.6	3	6	177.02	174.70	560.33
		0.4	3	6	87.24	85.18	137.33
		0.2	3	6	12.52	12.52	28.62
50	10	0.8	3	6	2813.40	TILIM	TILIM
		0.6	3	6	339.67	21.52	515.97
		0.4	3	6	57.54	79.35	109.25
		0.2	3	6	10.60	9.87	8.05

These findings are consistent with previous hub location studies showing that additional operational constraints generally increase model complexity and computational effort, particularly for large-scale instances. Unlike the classical single allocation hub location formulation, however, the proposed models explicitly regulate spoke allocation while simultaneously minimizing transportation cost. Consequently, the proposed constraints provide improved structural control with acceptable computational performance for small and medium-sized instances, although larger problems may benefit from more advanced solution approaches.

3.2.2. Objective Function (Total Cost)

This section analyses the impact of imposing lower bound constraints and combined lower and upper bound constraints on the total transportation cost in the single allocation hub location problem. The results for the CAB and TN datasets are reported in Table 3 and Table 4, respectively. The results show that imposing lower bound and combined lower and upper bound constraints on hub–spoke allocations increases the total transportation cost compared with the basic model. This is expected, as the additional constraints restrict the feasible solution space, thereby limiting the ability of the model to achieve the lowest possible cost. To quantify this effect, the percentage increase in total cost relative to the basic formulation was calculated. For the CAB dataset, the lower-bound model increases the total cost by an average of 1.23%, while the combined lower-and-upper-bound model increases it to 1.38%.

Table 3. Total cost for CAB

N	p	α	L	U	Total cost		
					Basic	With L	With L and U
25	4	0.8	3	6	1087.66	1087.66	1089.06
		0.6	3	6	939.21	939.21	942.97
		0.4	3	6	787.52	787.52	792.72
		0.2	3	6	629.63	629.63	636.72
25	6	0.8	2	5	991.00	991.00	991.00
		0.6	2	5	828.05	833.47	833.47
		0.4	2	5	659.79	665.34	665.34
		0.2	2	5	491.03	496.40	496.40
25	6	0.8	3	5	991.00	993.67	993.67
		0.6	3	5	828.05	835.58	835.58
		0.4	3	5	659.79	670.39	670.39
		0.2	3	5	491.03	500.27	500.27
25	8	0.8	2	5	929.03	948.42	948.42
		0.6	2	5	763.46	785.64	785.64
		0.4	2	5	589.03	616.67	616.67
		0.2	2	5	414.61	447.70	447.70

Table 4. Total cost for TN

N	p	α	L	U	Total cost		
					Basic	With L	With L and U
40	6	0.8	4	8	19787059940.80	20008214104.00	20008214104.00
		0.6	4	8	16873104093.40	17058328558.20	17121901309.20
		0.4	4	8	13498290621.80	13621535968.00	13766424606.80
		0.2	4	8	10002473024.80	10101658140.80	10295935718.80
40	6	0.8	3	7	19787059940.80	19841284692.20	19866412937.60
		0.6	3	7	16873104093.40	16931993983.20	17035099650.00
		0.4	3	7	13498290621.80	13530712838.60	13886336511.00
		0.2	3	7	10002473024.80	10021758244.80	10470058802.40
40	8	0.8	3	6	18596408589.40	18890640780.00	18906987370.40
		0.6	3	6	15317009163.20	15555138928.20	15594625317.00
		0.4	3	6	11849478030.60	12049061581.40	12049061581.40
		0.2	3	6	8270945773.20	8434330693.20	8434330693.20
40	8	0.8	2	5	18596408589.40	18702026441.40	18902975687.20
		0.6	2	5	15317009163.20	15400561808.80	15625546977.60
		0.4	2	5	11849478030.60	11898171685.20	12121684026.80
		0.2	2	5	8270945773.20	8287517815.80	8542622123.00
50	8	0.8	5	7	28640655417.80	29059708989.00	29059708989.00
		0.6	5	7	23852407181.00	24323160982.60	24323160982.60
		0.4	5	7	18972505376.00	19334751656.60	19334751656.60
		0.2	5	7	13691430217.40	14139814314.60	14139814314.60
50	8	0.8	4	7	28640655417.80	TILIM	TILIM
		0.6	4	7	23852407181.00	24088495585.80	24122813205.20
		0.4	4	7	18972505376.00	19099867491.00	19104530096.40
		0.2	4	7	13691430217.40	13790132352.80	13814143116.20
50	8	0.8	3	6	28640655417.80	28681867458.00	28895335110.40
		0.6	3	6	23852407181.00	23873262077.60	24175097200.00
		0.4	3	6	18972505376.00	18972505376.00	19110786780.60
		0.2	3	6	13691430217.40	13691430217.40	13916719864.80
50	10	0.8	3	6	27610794995.20	TILIM	TILIM
		0.6	3	6	22701437193.40	23384165804.00	22826079657.60
		0.4	3	6	17508523581.60	17629693372.60	17629693372.60
		0.2	3	6	12134709694.20	12211021516.80	12211021516.80

Similarly, for the TN dataset, the average cost increases are 0.99% and 1.52%, respectively. These results indicate that the additional upper-bound constraint provides greater structural control with only a marginal increase in transportation cost. Nevertheless, the increase remains small across both datasets, indicating that the proposed spoke allocation constraints require only limited

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adjustments to the optimal solutions obtained from the classical formulation. This observation is further supported by several instances in which the basic and constrained formulations produce identical objective values, showing that the optimal solution of the basic formulation already satisfies the imposed spoke allocation limits. Unlike the classical single allocation hub location problem, which minimizes transportation cost without explicitly regulating spoke allocation, the proposed formulations improve hub utilization and network structure while incurring only a modest increase in transportation cost. These findings demonstrate that meaningful structural improvements can be achieved with an average cost increase of less than 2% across both benchmark datasets.

3.2.3. Network Structure

This section analyses the impact of imposing lower bound constraints and combined lower and upper bound constraints on the network structure in the single allocation hub location problem. The results for the CAB and TN datasets are reported in Table 5, Table 6 and Table 7, respectively.

Table 5. Network Structure for CAB

N	p	α	L	U	Hub locations			Number of spokes allocated to hub		
					Basic	With L	With L and U	Basic	With L	With L and U
25	4	0.8	3	6	1, 4, 12, 18	1, 4, 12, 18	1, 4, 12, 18	6, 7, 3, 5	6, 7, 3, 5	6, 6, 3, 6
		0.6	3	6	1, 4, 12, 17	1, 4, 12, 17	1, 4, 12, 18	6, 7, 3, 5	6, 7, 3, 5	6, 6, 3, 6
		0.4	3	6	1, 4, 12, 17	1, 4, 12, 17	1, 4, 12, 17	6, 7, 3, 5	6, 7, 3, 5	6, 6, 3, 6
		0.2	3	6	4, 12, 17, 24	4, 12, 17, 24	4, 12, 16, 17	9, 3, 5, 4	9, 3, 5, 4	6, 4, 6, 5
25	6	0.8	2	5	1, 4, 6, 7, 12, 17	1, 4, 6, 7, 12, 17	1, 4, 6, 7, 12, 17	4, 3, 3, 2, 3, 4	4, 3, 3, 2, 3, 4	4, 3, 3, 2, 3, 4
		0.6	2	5	4, 6, 7, 12, 14, 17	4, 6, 7, 12, 17, 24	4, 6, 7, 12, 17, 24	4, 4, 3, 3, 1, 4	4, 3, 3, 3, 4, 2	4, 3, 3, 3, 4, 2
		0.4	2	5	4, 6, 7, 12, 14, 17	4, 6, 7, 12, 17, 24	4, 6, 7, 12, 17, 24	4, 4, 3, 3, 1, 4	3, 3, 4, 3, 4, 2	3, 3, 4, 3, 4, 2
		0.2	2	5	4, 6, 7, 12, 14, 17	4, 6, 7, 12, 17, 24	4, 6, 7, 12, 17, 24	3, 4, 4, 3, 1, 4	3, 3, 4, 3, 4, 2	3, 3, 4, 3, 4, 2
25	6	0.8	3	5	1, 4, 6, 7, 12, 17	1, 4, 6, 7, 12, 17	1, 4, 6, 7, 12, 17	4, 3, 3, 2, 3, 4	3, 3, 3, 3, 3, 4	3, 3, 3, 3, 3, 4
		0.6	3	5	4, 6, 7, 12, 14, 17	1, 4, 6, 7, 12, 17	1, 4, 6, 7, 12, 17	4, 4, 3, 3, 1, 4	3, 3, 3, 3, 3, 4	3, 3, 3, 3, 3, 4
		0.4	3	5	4, 6, 7, 12, 14, 17	4, 6, 7, 12, 17, 24	4, 6, 7, 12, 17, 24	4, 4, 3, 3, 1, 4	3, 3, 3, 3, 4, 3	3, 3, 3, 3, 4, 3
		0.2	3	5	4, 6, 7, 12, 14, 17	4, 6, 7, 12, 17, 24	4, 6, 7, 12, 17, 24	3, 4, 4, 3, 1, 4	3, 3, 3, 3, 4, 3	3, 3, 3, 3, 4, 3
25	8	0.8	2	5	1, 4, 6, 7, 8, 12, 17, 25	1, 4, 6, 7, 11, 12, 17, 25	1, 4, 6, 7, 11, 12, 17, 25	4, 3, 3, 1, 1, 2, 1, 2	2, 2, 2, 2, 2, 3, 2, 2	2, 2, 2, 2, 2, 3, 2, 2
		0.6	2	5	1, 4, 6, 7, 12, 14, 17, 22	4, 7, 9, 11, 12, 17, 24, 25	4, 7, 9, 11, 12, 17, 24, 25	2, 3, 3, 2, 1, 1, 4, 1	2, 2, 2, 2, 3, 2, 2, 2	2, 2, 2, 2, 3, 2, 2, 2
		0.4	2	5	1, 4, 6, 7, 12, 14, 17, 22	4, 7, 9, 11, 12, 17, 24, 25	4, 7, 9, 11, 12, 17, 24, 25	2, 3, 3, 2, 1, 1, 4, 1	2, 2, 2, 2, 3, 2, 2, 2	2, 2, 2, 2, 3, 2, 2, 2
		0.2	2	5	1, 4, 6, 7, 12, 14, 17, 22	4, 7, 9, 11, 12, 17, 24, 25	4, 7, 9, 11, 12, 17, 24, 25	2, 3, 3, 2, 1, 1, 4, 1	2, 2, 2, 2, 3, 2, 2, 2	2, 2, 2, 2, 3, 2, 2, 2

The results show that imposing lower bound and combined lower and upper bound constraints has a substantial impact on the resulting network structure. The effect is observed not only in the distribution of spokes assigned to each hub, but also in several cases in the selected hub locations. To illustrate the effect of the proposed constraints on spoke allocation, Fig. 2 presents a representative TN instance with $N = 40$, $p = 8$, $\alpha = 0.6$, $L = 3$, and $U = 6$. Fig. 2a shows the basic formulation, Fig. 2b shows the formulation with the lower bound constraint, and Fig. 2c shows the formulation with both lower and upper bound constraints.

Table 6. Network structure for TN (N = 40)

N	p	α	L	U	Hub locations			Number of spokes allocated to hub		
					Basic	With L	With L and U	Basic	With L	With L and U
40	6	0.8	4	8	1,3,6,16,24,34	1,3,6,16,24,34	1, 3, 6, 16, 24, 34	6,7,8,3,8,2	6,5,7,4,8,4	6, 5, 7, 4, 8, 4
		0.6	4	8	1,3,6,23,34,35	1,6,16,23,32,34	1, 6, 16, 23, 32, 34	4,7,8,10,3,2	4,7,4,10,5,4	5, 8, 4, 8, 5, 4
		0.4	4	8	1,6,12,32,34,35	1,6,12,32,34,35	1, 6, 12, 32, 34, 35	4,9,10,4,5,2	4,8,10,4,4,4	6, 8, 8, 4, 4, 4
		0.2	4	8	1,6,15,25,34,35	1, 6, 15, 25, 34, 35	1, 6, 12, 15, 34, 35	4,8,4,11,5,2	4, 7, 4, 11, 4, 4	6, 8, 8, 4, 4, 4
40	6	0.8	3	7	1,3,6,16,24,34	1, 3, 6, 16, 24, 34	1, 3, 6, 16, 24, 34	6,7,8,3,8,2	6, 7, 7, 3, 8, 3	7, 7, 7, 3, 7, 3
		0.6	3	7	1,3,6,23,34,35	1, 3, 6, 23, 34, 35	1, 3, 6, 25, 34, 35	4,7,8,10,3,2	4, 6, 8, 10, 3, 3	7, 7, 7, 7, 3, 3
		0.4	3	7	1,6,12,32,34,35	1, 6, 12, 32, 34, 35	1, 3, 6, 25, 34, 35	4,9,10,4,5,2	4, 9, 10, 4, 4, 3	7, 7, 7, 7, 3, 3
		0.2	3	7	1,6,15,25,34,35	1, 6, 15, 25, 34, 35	1, 6, 12, 15, 34, 35	4,8,4,11,5,2	4, 8, 4, 11, 4, 3	7, 7, 7, 5, 5, 3
40	8	0.8	3	6	1, 3, 6, 16, 23, 24, 34, 35	1, 3, 6, 16, 23, 24, 34, 35	1, 3, 6, 16, 23, 24, 34, 35	4, 5, 8, 3, 4, 5, 2, 1	4, 3, 7, 3, 4, 5, 3, 3	4, 3, 6, 3, 4, 6, 3, 3
		0.6	3	6	1, 6, 16, 21, 25, 32, 34, 35	1, 6, 16, 21, 25, 32, 34, 35	1, 6, 16, 23, 24, 32, 34, 35	4, 8, 4, 4, 5, 4, 2, 1	4, 7, 3, 4, 5, 3, 3, 3	4, 6, 3, 4, 6, 3, 3, 3
		0.4	3	6	1, 6, 16, 21, 25, 32, 34, 35	1, 6, 16, 21, 25, 32, 34, 35	1, 6, 16, 21, 25, 32, 34, 35	4, 7, 4, 4, 6, 4, 2, 1	4, 6, 3, 4, 6, 3, 3, 3	4, 6, 3, 4, 6, 3, 3, 3
		0.2	3	6	1, 6, 15, 16, 21, 25, 34, 35	1, 6, 16, 21, 25, 32, 34, 35	1, 6, 16, 21, 25, 32, 34, 35	3, 7, 4, 4, 5, 6, 2, 1	3, 6, 3, 5, 6, 3, 3, 3	3, 6, 3, 5, 6, 3, 3, 3
40	8	0.8	2	5	1, 3, 6, 16, 23, 24, 34, 35	1, 3, 6, 16, 23, 24, 34, 35	1, 3, 6, 16, 23, 24, 34, 35	4, 5, 8, 3, 4, 5, 2, 1	4, 5, 8, 2, 4, 5, 2, 2	4, 5, 5, 4, 5, 5, 2, 2
		0.6	2	5	1, 6, 16, 21, 25, 32, 34, 35	1, 6, 7, 16, 21, 25, 34, 35	1, 6, 16, 23, 24, 32, 34, 35	4, 8, 4, 4, 5, 4, 2, 1	4, 9, 2, 4, 4, 5, 2, 2	5, 5, 4, 5, 5, 4, 2, 2
		0.4	2	5	1, 6, 16, 21, 25, 32, 34, 35	1, 6, 7, 16, 21, 25, 34, 35	1, 6, 16, 21, 25, 32, 34, 35	4, 7, 4, 4, 6, 4, 2, 1	4, 8, 2, 4, 4, 6, 2, 2	5, 5, 4, 5, 5, 4, 2, 2
		0.2	2	5	1, 6, 15, 16, 21, 25, 34, 35	1, 6, 7, 16, 21, 25, 34, 35	1, 6, 7, 16, 21, 25, 34, 35	3, 7, 4, 4, 5, 6, 2, 1	3, 8, 2, 4, 5, 6, 2, 2	5, 5, 2, 5, 5, 5, 3, 2

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It can be observed that the basic formulation produces several hubs with only one or two spokes, whereas the lower bound formulation eliminates these underutilized hubs by ensuring that each hub serves at least three spokes. The addition of the upper bound further modifies the hub configuration while maintaining the prescribed spoke allocation limits, resulting in a more controlled distribution of spokes among the selected hubs.

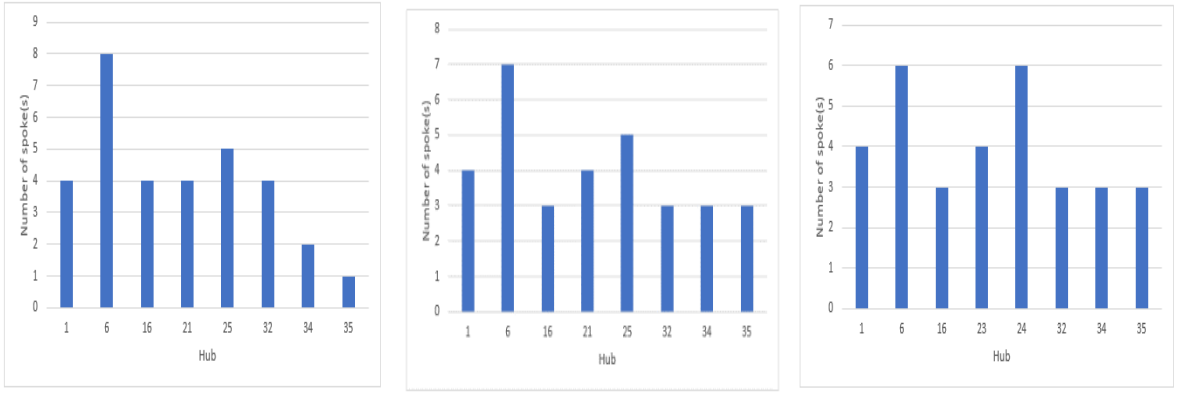
Table 7. Network structure for TN (N = 50)

N	p	α	L	U	Hub locations			Number of spokes allocated to hub		
					Basic	With L	With L and U	Basic	With L	With L and U
50	8	0.8	5	7	1, 3, 6, 16, 24, 34, 35, 44	1, 3, 6, 24, 41, 42, 44, 45	1, 3, 6, 24, 41, 42, 44, 45	4, 8, 9, 4, 5, 2, 2, 8	5, 5, 5, 5, 5, 5, 7, 5	5, 5, 5, 5, 5, 5, 7, 5
		0.6	5	7	1, 3, 6, 16, 23, 25, 34, 35	1, 6, 23, 25, 26, 34, 42, 45	1, 6, 23, 25, 26, 34, 42, 45	5, 7, 9, 4, 8, 4, 2, 3	5, 5, 7, 5, 5, 5, 5, 5	5, 5, 7, 5, 5, 5, 5, 5
		0.4	5	7	1, 6, 16, 23, 25, 32, 34, 35	1, 6, 16, 23, 25, 34, 35, 42	1, 6, 16, 23, 25, 34, 35, 42	5, 9, 5, 7, 6, 4, 3, 3	5, 5, 5, 7, 5, 5, 5, 5	5, 5, 5, 7, 5, 5, 5, 5
		0.2	5	7	1, 6, 15, 16, 21, 25, 34, 35	1, 6, 16, 21, 25, 34, 35, 42	1, 6, 16, 21, 25, 34, 35, 42	4, 9, 4, 5, 8, 6, 3, 3	5, 5, 5, 7, 5, 5, 5, 5	5, 5, 5, 7, 5, 5, 5, 5
50	8	0.8	4	7	1, 3, 6, 16, 24, 34, 35, 44	TILIM	TILIM	4, 8, 9, 4, 5, 2, 2, 8	TILIM	TILIM
		0.6	4	7	1, 3, 6, 16, 23, 25, 34, 35	1, 3, 6, 16, 23, 25, 34, 35	1, 3, 6, 16, 23, 24, 34, 35	5, 7, 9, 4, 8, 4, 2, 3	5, 5, 8, 4, 8, 4, 4, 4	5, 5, 7, 4, 7, 6, 4, 4
		0.4	4	7	1, 6, 16, 23, 25, 32, 34, 35	1, 6, 16, 23, 25, 32, 34, 35	1, 6, 16, 23, 25, 34, 35, 42	5, 9, 5, 7, 6, 4, 3, 3	5, 8, 4, 7, 6, 4, 4, 4	5, 6, 5, 7, 6, 4, 4, 5
		0.2	4	7	1, 6, 15, 16, 21, 25, 34, 35	1, 6, 15, 16, 21, 25, 34, 35	1, 6, 16, 21, 25, 34, 35, 42	4, 9, 4, 5, 8, 6, 3, 3	4, 8, 4, 4, 8, 6, 4, 4	4, 5, 5, 7, 7, 4, 4, 6
50	8	0.8	3	6	1, 3, 6, 16, 24, 34, 35, 44	1, 3, 6, 16, 24, 34, 35, 44	1, 3, 6, 24, 41, 42, 44, 45	4, 8, 9, 4, 5, 2, 2, 8	4, 7, 9, 3, 5, 3, 3, 8	6, 6, 6, 5, 6, 3, 6, 4
		0.6	3	6	1, 3, 6, 16, 23, 25, 34, 35	1, 3, 6, 16, 23, 25, 34, 35	1, 6, 16, 23, 25, 34, 35, 42	5, 7, 9, 4, 8, 4, 2, 3	5, 7, 9, 3, 8, 4, 3, 3	5, 6, 6, 6, 6, 3, 4, 6
		0.4	3	6	1, 6, 16, 23, 25, 32, 34, 35	1, 6, 16, 23, 25, 32, 34, 35	1, 6, 16, 21, 25, 34, 35, 42	5, 9, 5, 7, 6, 4, 3, 3	5, 9, 5, 7, 6, 4, 3, 3	6, 6, 5, 6, 6, 3, 4, 6
		0.2	3	6	1, 6, 15, 16, 21, 25, 34, 35	1, 6, 15, 16, 21, 25, 34, 35	1, 6, 16, 21, 25, 34, 35, 42	4, 9, 4, 5, 8, 6, 3, 3	4, 9, 4, 5, 8, 6, 3, 3	6, 6, 5, 6, 6, 3, 4, 6
50	10	0.8	3	6	1, 3, 6, 16, 25, 34, 35, 38, 42, 44	TILIM	TILIM	4, 7, 6, 4, 3, 2, 2, 4, 0, 8	TILIM	TILIM
		0.6	3	6	1, 3, 6, 7, 16, 23, 25, 34, 35, 42	1, 6, 15, 16, 21, 25, 34, 35, 42, 46	1, 3, 6, 16, 21, 25, 34, 35, 42, 44	5, 5, 8, 0, 4, 8, 4, 2, 3, 1	3, 7, 3, 5, 5, 5, 3, 3, 3, 3	4, 6, 6, 3, 3, 5, 3, 3, 3, 4
		0.4	3	6	1, 6, 16, 21, 25, 32, 34, 35, 42, 46	1, 6, 7, 16, 21, 25, 34, 35, 42, 46	1, 6, 7, 16, 21, 25, 34, 35, 42, 46	2, 7, 6, 6, 6, 4, 2, 3, 1, 3	3, 5, 3, 5, 6, 6, 3, 3, 3, 3	3, 5, 3, 5, 6, 6, 3, 3, 3, 3
		0.2	3	6	1, 6, 7, 16, 21, 25, 34, 35, 42, 46	1, 6, 7, 16, 21, 25, 34, 35, 42, 46	1, 6, 7, 16, 21, 25, 34, 35, 42, 46	2, 6, 3, 5, 6, 6, 3, 3, 3, 3	3, 5, 3, 5, 6, 6, 3, 3, 3, 3	3, 5, 3, 5, 6, 6, 3, 3, 3, 3

For the CAB dataset, the proposed constraints improve the hub-and-spoke structure by eliminating hubs with very few spokes and limiting excessive spoke concentration. For example, when $p = 4$, the basic formulation assigns up to seven or nine spokes to a single hub, whereas the bounded formulation limits this number to six. In several CAB instances, the lower-bound and combined lower-and-upper-bound formulations produce identical solutions, indicating that the upper-bound constraint is non-binding once the minimum spoke requirement is satisfied. The structural impact is even more pronounced for the TN dataset, where the basic formulation frequently produces hubs serving zero, one, or two spokes, while others serve up to eight to eleven spokes. The proposed constraints eliminate these weak hub configurations and reduce excessive concentration, resulting in a more controlled distribution of spokes among hubs.

These findings highlight the distinction between controlling hub capacity and regulating the number of spokes assigned to each hub. While hub capacity constraints regulate the volume of flow handled by each hub Alumur & Kara (2008); Farahani et al. (2013), spoke allocation constraints directly control the number of assigned spokes. Alumur & Kara (2008) incorporated minimum spoke allocation requirements into a hub location-routing problem. In contrast, the present study evaluates the structural effects of lower and upper spoke allocation bounds within the conventional single-allocation hub location problem.

An important observation is that the proposed constraints influence not only spoke allocation decisions but also hub location decisions. This effect is particularly apparent for the TN dataset, where the bounded formulations frequently select different hub sets from those obtained using the basic formulation. This occurs because the additional spoke allocation constraints require the optimization model to reconsider hub selections that would otherwise minimize transportation cost but do not satisfy the prescribed structural requirements. As a result, the model may either redistribute spokes among existing hubs or select alternative hub locations to obtain a feasible and structurally desirable network. This finding indicates that spoke allocation bounds affect both assignment decisions and the location-allocation trade-off. In classical hub location problems, hub locations and node allocations are jointly optimized to minimize transportation costs (Alumur & Kara, 2008; Contreras, 2021). Additional allocation bounds may alter hub locations or redistribute spokes. However, in several test cases based on the Civil Aeronautics Board (CAB) dataset, the lower-bound and combined-bound formulations produce identical solutions, indicating that the upper-bound constraint is not always binding.



a b c

Fig. 2. Number of spokes assigned to each hub for a representative TN instance

Unlike the classical single allocation hub location formulation, which determines hub locations solely on the basis of transportation cost, the proposed formulations explicitly regulate hub utilization through spoke allocation limits. Consequently, the resulting networks not only maintain high-cost efficiency but also exhibit improved structural characteristics by avoiding both underutilized hubs and excessive concentration of spokes. From a practical perspective, these characteristics may facilitate more effective utilization of hub facilities and produce network configurations that are better aligned with operational planning requirements.

3.3. Managerial Insights

The computational results provide several managerial insights regarding the design of hub-and-spoke networks under bounded spoke allocation. First, the results indicate that imposing bounds on the number of spokes per hub leads to only a modest increase in total transportation cost. On average, the lower bound constraint increases cost by approximately 1.23% for the CAB dataset and 0.99% for the TN dataset, while the combined lower and upper bounds increase cost by about 1.38% and 1.52%, respectively. These relatively small increases suggest that enforcing structural constraints on hub utilization can be achieved with limited cost penalties. Second, the network structure analysis shows that the lower bound constraint plays an important role in eliminating underutilized hubs. In the basic

formulation, some hubs may serve only one or even zero spokes, which contradicts the intended role of hubs as consolidation points. By imposing a minimum number of spokes, each selected hub is ensured to serve a meaningful number of non-hub nodes. From a managerial perspective, this avoids inefficient investments in hub facilities that do not significantly contribute to flow consolidation (Pajala et al., 2026).

Third, the introduction of an upper bound helps prevents excessive concentration of spokes on a small number of hubs. In the basic model, certain hubs may dominate the network by serving a disproportionately large number of spokes, potentially leading to congestion and operational inefficiencies. The upper bound constraint distributes the workload more evenly across hubs, resulting in a more manageable network structure. This is particularly relevant in real-world applications where hubs have limitations in handling connections due to capacity, workforce, or infrastructure constraints. Fourth, the results show that the proposed constraints may influence not only the allocation of spokes but also the selection of hub locations. In several instances, different sets of hubs are chosen when bounds are imposed, indicating that structural requirements can alter strategic hub location decisions.

Finally, the findings reveal a clear trade-off between cost efficiency and structural control. While the basic model achieves the lowest cost, it may produce impractical or undesirable network configurations. In contrast, the bounded models produce more structured and operationally meaningful solutions, at the expense of a small increase in cost. Therefore, decision-makers can use the proposed bounds as policy parameters to control hub utilization according to operational priorities, such as avoiding underutilized hubs or limiting congestion at major hubs. The findings support the fundamental role of hubs as flow consolidation facilities described in previous hub location studies (Alumur et al., 2021; Contreras, 2021; Contreras & O'Kelly, 2019; Li et al., 2025; Setiawan et al., 2025a, 2025b). By explicitly regulating spoke allocation, the proposed formulations extend the classical single allocation hub location problem to better reflect practical operational considerations while incurring only a modest increase in transportation cost. More importantly, the results fulfill the objective of this study by demonstrating that bounded spoke allocation influences not only computational performance and transportation cost but also the resulting network structure and strategic hub location decisions.

4. Conclusion

This paper investigates the impact of imposing explicit bounds on hub–spoke allocations in the single allocation hub location problem. Motivated by the limitations of standard formulations, which may produce underutilized or overly dominant hubs, this study considers two constraint settings: a lower bound to ensure minimum hub utilization and combined lower and upper bounds to regulate both underutilization and excessive concentration. The computational results demonstrate that the proposed formulations successfully improve the structural properties of hub-and-spoke networks. The lower bound eliminates weak hubs with very few spokes, while the upper bound limits excessive concentration of spokes on a small number of hubs. These structural improvements are achieved with only a modest increase in total transportation cost, averaging approximately 0.99% – 1.52% across both benchmark datasets. The results also show that the proposed constraints may influence hub location decisions and that their computational impact depends on problem size, reducing solution time for some small instances while increasing computational effort for larger problems.

From a scientific perspective, this study extends the classical single allocation hub location formulation by explicitly incorporating bounded spoke allocation constraints and systematically evaluating their effects on computational performance, transportation cost and network structure. From a practical perspective, the proposed formulations provide decision-makers with simple and interpretable parameters for controlling hub utilization, allowing network structures to better reflect operational requirements while incurring only a modest increase in transportation cost. The proposed formulations are limited to the deterministic single allocation hub location problem and do not explicitly consider uncertainty in demand or transportation costs. In addition, the proposed constraints increase the computational difficulty for large-scale instances, indicating that more efficient solution approaches may be required for practical large-scale applications. These limitations provide several

directions for future research. The proposed constraints may be extended to other hub location variants, such as multiple allocation and incomplete hub location problems. Future studies may also investigate advanced exact or heuristic solution methods for larger-scale instances and incorporate uncertainty in demand or transportation cost to better represent real-world hub network problems.

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