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A Bi-Level Programming Model for the Integrated Problem of Low Carbon Supplier Selection and Transportation

Hongli Zhu [1,*], Congcong Liu [2] and Yongming Song [1]

[1] School of Business Administration, Shandong Technology and Business University, Yantai 264005, China
[2] School of Electrical Engineering, Shandong University, Jinan 250061, China
* Correspondence: honglizhu@sdtbu.edu.cn

Abstract: In this paper, we investigate an integrated problem of low-carbon supplier selection and transportation. The supplier selection decision depends on the location and energy consumption level of batching plants at the manufacturing stage. Meanwhile, ready-mixed concrete is allocated and delivered to construction sites by concrete mixer trucks at the transportation stage. A bi-level programming model for the integrated problem is established. The bi-level optimization problem is transformed into a single-level problem by KKT (Karush–Kuhn–Tucker) optimality conditions. In order to validate the proposed model, a case study is conducted based on real-world problems. Experimental results show that the proposed method efficiently solves the integrated problem and the model can not only reduce carbon emissions but also optimize transportation time.

Keywords: bi-level programming; low carbon; integrated problem

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1. Introduction

With the rapid development of urbanization and industrialization, the construction of infrastructure has a severe impact on air pollution [1]. According to an analysis of the International Energy Agency (IEA), greenhouse gas emissions in buildings and the transport sector together represented in 2019 over half of global emissions, with transport comprising 27%, followed by buildings (25%). The increasing requirements of construction lead to a large demand for building materials. As the most widely used man-made building material, concrete consumption is approximately 1 ton for every human being each year, which produces tremendous carbon dioxide emissions [2].

Concrete CO_2 emissions result from energy consumption not only in the production stage but also in the transport phase to the construction site [3]. Generally, concrete is made up of cement, water, and aggregates. Concrete batching and mixing is commonly carried out at concrete batching plants, located in different positions around the city. The mixing equipment is powered by electricity, which is the main source of emissions. Therefore, the energy consumption level of mixing equipment is the most crucial factor of emissions generated during the concrete production stage. After the production process, the concrete is transported to construction sites by a concrete mixer truck. The diesel fuel consumption of concrete transport is also a contributor to CO_2 emissions [1]. In order to reduce concrete CO_2 emissions, it is necessary to optimize the integrated problem of concrete production and transport.

There are two significant decisions: supplier selection and transportation planning, which are interdependent. The selection of concrete batching plants is a strategic decision that will have a long-term impact on the performance. This decision to choose the energy consumption level and facility location can influence not only the environment cost but also transportation times.

In the past few decades, facility location problems have attracted more and more attention. Farahani et al. conducted a comprehensive review on covering problems in facility locations [4]. Extending the classical facility location problems, Ortiz-Astorquiza et al. presented a survey of formulations, algorithms, and applications for multi-level facility location problems [5]. Puerto et al., provided an updated literature review of extensive facility location problems in networks [6]. A lot of research branches have been intensively investigated. Emirhüseyinoğlu and Ekici considered the facility location decision problem with supplier selection [7]. Arıoğlu et al. studied supplier selection and evaluation for the production of concrete in a large construction project [8]. Another research focus is the transportation or dispatching problem. Ready-mixed concrete is supplied to construction sites from batching plants along planned roads. Narayanan et al. introduced the delivery planning problem of ready-mixed concrete, which is formulated as a mixed-integer programming problem. Lagrangian relaxation is used to solve the concrete dispatching problem [9]. Maghrebi et al., addressed the large-scale ready-mixed concrete delivery problem and developed a column generation-based algorithm [10].

In the above-mentioned studies, facility location and transportation problems were considered separately. Additionally, it is of great importance to investigate the integrated problem of facility location and transportation [11]. There have been a few related works proposed from the supply chain perspective. Tezenji et al. presented an integrated model for supplier location-selection and order allocation with distance-based transportation cost [12]. Das et al., explored an integration problem between the facility location problem and transportation with the goal of determining optimum places for facilities and minimizing transportation cost [13]. Carlo et al., proposed an extended transportation location problem where the number of new facilities is a decision variable [14]. It is noted that the studies focused on the economic cost.

Recently, researchers have attempted to establish the integrated model from a low-carbon perspective. Leng et al. proposed a regional low-carbon location-routing problem with a bi-objective model. The total logistics cost and vehicle waiting time were both considered as objectives [15]. Hemmati and Pasandideh investigated a mixed-integer nonlinear program for the suppler location, supplier selection, and order allocation problem with green constraints. A bi-objective model was established by taking the total cost as the first objective and CO_2 emissions as the second objective [16]. Kang et al. designed a novel bi-objective model for the supplier selection and inventory allocation planning problem with carbon trading [17]. Leng et al., developed a low-carbon location-routing problem for cold chain logistics. A novel bi-objective model was established with the goal of economic costs and environmental benefits [18].

However, the facility location problems are strategic decisions from the management point of view. Meanwhile, transportation planning issues are tactical decisions. Bi-level programming is applicable to solve these issues [19,20]. Wang et al., explored a bi-level programming approach to the location-routing problem with cargo splitting under low-carbon policies [21].

From the perspective of model building, the supplier selection decisions for the integrated problem are related to the number and location of plants, warehouses, or other facilities without determining the level of production energy consumption. Accordingly, we investigated the low-carbon integrated problem of concrete supplier selection and transportation planning in terms of selecting the energy consumption level of supplier equipment, determining the location of the concrete supplier, and planning the transportation of ready-mixed concrete. As mentioned above, a bi-level programming model [22] was established to deal with the strategic and tactical decision problems.

The main contributions of this paper are threefold. First, we propose an integrated problem of supplier selection and transportation from a low-carbon perspective. The CO_2 emissions are generated not only in the production stage but also in the transportation stage. Second, a bi-level programming model is formulated to optimize both strategic and tactical decisions. The upper level is to minimize total CO_2 emissions according to environmental criteria, whereas the lower-level model is designed to minimize the transportation time from the perspective of economy. Third, the bi-level optimization problem is transformed into a single-level problem through KKT conditions and dual theory.

The remainder of the paper is structured as follows. In Section 2, we describe the problem and present the mathematical model. In Section 3, we provide the solution method. In Section 4, a case study is conducted. In Section 5, we provide some concluding remarks.

2. Problem Description and Mathematical Model

2.1. Problem Description

The problem is described as follows. An integrated problem of low-carbon concrete supplier selection and transportation (IPLCCSST) is considered. At the strategic decision level, the construction enterprise needs to select several concrete batching plants for serving construction sites, which are located in different positions around the city. Generally, the concrete prices of different plants in a certain area are the same. The supplier selection decision depends on the location and energy consumption level of batching plants. At the tactical decision level, the batching plants are allocated to construction sites to satisfy their demands. After production, the allocated ready-mixed concrete can be delivered to corresponding construction sites by a concrete mixer truck. According to the concrete setting time, it is not allowed to deliver all concrete at once.

The following assumptions are considered:

1. The locations of the concrete batching plants and construction sites are known.
2. The capacities of the batching plants are known. The demand of each construction site is known, which should be supplied by one batching plant.
3. There are certain concrete mixer trucks initially available at each batching plant.
4. The distance and travelling time between plant and construction site is known. Due to the different speed limit, distance and time are not in direct proportion.
5. The truck unloading time is ignored.
6. We define volume as a unit term to measure the amount of concrete, which equals the capacity of one concrete mixer truck.
7. The energy consumption level of the batching plant is known.
8. The carbon dioxide emissions generated at the production stage are related to the energy consumption level and capacity.
9. The carbon dioxide emissions in the transportation phase are associated with distance.

As described above, the upper-level decision-maker develops the supplier selection strategy to optimize the environmental criteria by minimizing carbon dioxide emissions caused in the production and transportation stage from the perspective of society, whereas the low-level decision-maker formulates the transportation schedule to improve delivery efficiency by minimizing concrete delivery time.

2.2. Evaluation of Carbon Dioxide Emissions

The carbon dioxide emissions are generated in both the concrete production and transportation stages. The evaluation of CO_2 emissions is presented as follows:

(1) Carbon Dioxide Emissions from Concrete Production

In the concrete production stage, the energy consumption is based on the energy consumption level and the capacity of the production batching plants. Hence, the amount of energy consumption in the production stage can be calculated by the following equation [23]:

$$\mathrm{EC} = \sum_i EL_i \times z_i \tag{1}$$

In this equation, EC represents the energy consumption of the concrete batching plant, whose units are standard coal equivalent corresponding to the energy produced by the combustion of 1 kg of coal (in kgce). EL_i denotes the energy consumption level of concrete batching plant i. z_i is amount of concrete produced at batching plant i.

Hence, the CO_2 emissions in the production stage can be calculated by the following equation [24]:

$$\mathrm{E}^{p}_{\mathrm{CO}_2} = EC \times EF_p \tag{2}$$

where EC is the total energy consumption of the concrete batching plant, and EF_p is the CO_2 emission factor in the production stage.

(2) Carbon Dioxide Emissions from Concrete Transportation

In the transportation phase, the CO_2 emissions are generated when the ready-mixed concrete is transported to construction sites by a concrete mixer truck. Due to the special type of vehicle, the following calculation equation is adopted [24]:

$$E^{t}_{\mathrm{CO}_2} = \mathrm{d}_{ij} \times ac \times EF_t \tag{3}$$

where d_{ij} is the distance between concrete batching plant i and construction site j, ac is the average fuel consumption of the concrete mixer truck, and EF_t is the CO_2 emission factor in the transportation stage.

2.3. The Bi-Level Programming Model for IPLCCSST

To develop the model, notations are defined as follows:

Sets:
I: set of candidate concrete batching plants
J: set of construction sites

Parameters:
d_{ij}: distance between concrete batching plant i and construction site j
p: number of selected concrete batching plants
d_j: demand of construction site j
s_i: capacity of concrete batching plant i
c: load capacity of the concrete mixer truck
t_{ij}: time of a shipment of concrete transported from batching plant i to construction site j by concrete mixer truck

Decision variables:
x_i: 1 if candidate batching plant i is selected to supply concrete
0 otherwise
y_{ij}: amount of shipments of concrete transported from batching plant i to construction site j by concrete mixer truck
z_i: amount of shipments of concrete supplied from batching plant i

With the notations above, we can formulate a bi-level programming model for the integrated problem of low-carbon concrete supplier selection and transportation (BIIPLCCSST) as follows:

The upper-level model (UBIIPLCCSST):
Objective function:

$$\min F_1 = \sum_i EL_i \times z_i \times c \times EF_p + \sum_i \sum_j y_{ij} \times c \times d_{ij} \times ac \times EF_t \tag{4}$$

subject to:

$$\sum_i x_i \leq p \tag{5}$$

$$\sum_i z_i = \sum_j d_j \tag{6}$$

$$z_i \leq s_i \tag{7}$$

$$x_i \in \{0,1\} \tag{8}$$

$$z_i \geq 0, z_i \in \mathbb{Z} \tag{9}$$

Equation (4) is the objective function of the upper model, which minimizes the total CO_2 emissions. The first term indicates the CO_2 emissions generated in the concrete production stage. The second term implies the CO_2 emissions in the transportation phase. Constraint (5) limits the number of selected concrete batching plants to p. Constraint (6) ensures that the sum of transportation volumes from all batching plants is equal to the total demand of all constructions site. Constraint (7) enforces that concrete batching plant capacities are not violated. Constraint (8) is a binary restriction. Constraint (9) defines the domains of the decision variables.

The lower-level model (LBIIPLCCSST):

Objective function:

$$\min F_2 = \sum_i \sum_j t_{ij} y_{ij} \tag{10}$$

subject to:

$$\sum_i y_{ij} = d_j, j = 1, 2, \ldots n \tag{11}$$

$$\sum_j y_{ij} = z_i, i = 1, 2, \ldots m \tag{12}$$

$$y_{ij} \leq M_1 x_i, i = 1, 2, \ldots m, j = 1, 2, \ldots n \tag{13}$$

$$y_{ij} \geq 0, y_{ij} \in \mathbb{Z} \tag{14}$$

Equation (10) is the objective function of lower-level model, which minimizes the total transportation time. Constraint (11) ensures that for each construction site, the total transportation volumes from all batching plants are equal to its demand, whereas constraint (12) guarantee that the total transportation volumes from each batching plant are equal to the supply of the plant. Constraint (13) imposes that construction sites can be served only from selected batching plants where M1 represents a large integer number. Constraint (14) is the variable domain constraints.

3. Solution Method

In order to solve the lower-level model, we relaxed the lower-level constraint (14) to the following:

$$y_{ij} \geq 0 \tag{15}$$

The problem (10)–(13) and (15) is denoted as relaxation-LBIIPLCCSST, which is a relaxation of LBIIPLCCSST. Let *A1*, *A2* be the coefficient matrix of constraints (10)–(12), respectively. Let *b1*, *b2* denote the right-hand side of constraints (10)–(12), respectively. Then, we present some results, which will be used in subsequent sections.

Lemma 1. *The polyhedron {constraints (11)–(13) and (15)} is integral.*

Proof. Recall that *A1* is totally unimodular, and *A2* is I. We can obtain that $\begin{bmatrix} A1 \\ A2 \end{bmatrix}$ is total unimodular [25]. As mentioned above, *b1* and *b2* are integral vectors. Due to Hoffman and Kruskal's theorem, it is easy to yield the result. □

Proposition 1. *The relaxation-LBIIPLCCSST and its duality equation have integral optimum solutions.*

Proof. Note that c is an integral vector. Direct from the fundamental properties of total unimodularity and integer linear programming [26], we can obtain the property of LBIIPLCCSST. □

Thereby, we provide a straightforward property for LBIIPLCCSST. The proof is omitted.

Corollary 1. *The LBIIPLCCSST can be optimally solved by the relaxation-LBIIPLCCSST.*

By Corollary 1, the lower-level model can be optimally solved by its relaxation problem. We obtain the dual problem of the relaxation-LBIIPLCCSST:

$$\max \sum_i z_i u_i + \sum_j d_j v_j + \sum_i \sum_j M_1 x_i r_{ij} \tag{16}$$

subject to:

$$u_i + v_j + r_{ij} \le t_{ij} \tag{17}$$

$$r_{ij} \le 0 \tag{18}$$

$$u_i, free \tag{19}$$

$$v_j, free \tag{20}$$

As the LBIIPLCCSST problem is linear, the bi-level optimization problem can be transformed into a single-level problem using the Karush–Kuhn–Tucker (KKT) optimality conditions. The equivalent single-level problem is formulated as follows.

$$\min \sum_i EL_i * z_i * EF_p + \sum_i \sum_j y_{ij} * d_{ij} * ac * EF_t \tag{21}$$

subject to:

$$\sum_i x_i \le p \tag{22}$$

$$\sum_i z_i = \sum_j d_j \tag{23}$$

$$z_i \le s_i \tag{24}$$

$$\sum_i y_{ij} = d_j \tag{25}$$

$$\sum_j y_{ij} = z_i \tag{26}$$

$$y_{ij} \le M_1 x_i \tag{27}$$

$$u_i + v_j + r_{ij} \le t_{ij} \tag{28}$$

$$r_{ij}(y_{ij} - M_1 x_i) = 0 \tag{29}$$

$$x_i \in \{0, 1\} \tag{30}$$

$$z_i \ge 0, z_i \in \mathbb{Z} \tag{31}$$

$$y_{ij} \ge 0 \tag{32}$$

$$r_{ij} \le 0 \tag{33}$$

$$u_i, free \tag{34}$$

$$v_j, free \tag{35}$$

Equation (21) is the objective function of the equivalent single-level model. Constraints (22)–(24), (30) and (31) are the constraints of the upper-level problem. Constraints (25)–(27) and (32) are the primal constraints of the relaxed lower-level problem, whereas constraints (28) and (33)–(35) are the dual constraints of the relaxed lower-level problem. Constraint (29) is the complementary slackness conditions, which guarantee the optimality of the relaxed lower-level problem.

However, the complementary slackness conditions are non-linear. In order to linearize the complementary conditions, the big-M reformulation is used as follows [27]: Add a binary variable δ_{ij} to the problem and append two additional constraints instead of the complementary conditions. We constructed the following big-M constraints:

$$r_{ij} \geq -M_2\delta_{ij} \tag{36}$$

$$y_{ij} - M_1x_i \geq -M_2(1-\delta_{ij}) \tag{37}$$

where M_2 is a large positive constant. Then the resulting linearized single-level formulation is obtained as follows:

$$\min \sum_i EL_i * z_i * EF_p + \sum_i \sum_j y_{ij} * d_{ij} * ac * EF_t \tag{38}$$

subject to:

$$\sum_i x_i \leq p \tag{39}$$

$$\sum_i z_i = \sum_j d_j \tag{40}$$

$$z_i \leq s_i \tag{41}$$

$$\sum_i y_{ij} = d_j \tag{42}$$

$$\sum_j y_{ij} = z_i \tag{43}$$

$$y_{ij} \leq M_1x_i \tag{44}$$

$$u_i + v_j + r_{ij} \leq t_{ij} \tag{45}$$

$$r_{ij} \geq -M_2\delta_{ij} \tag{46}$$

$$y_{ij} - M_1x_i \geq -M_2(1-\delta_{ij}) \tag{47}$$

$$x_i \in \{0,1\} \tag{48}$$

$$\delta_{ij} \in \{0,1\} \tag{49}$$

$$z_i \geq 0, z_i \in \mathbb{Z} \tag{50}$$

$$y_{ij} \geq 0 \tag{51}$$

$$r_{ij} \leq 0 \tag{52}$$

$$u_i, free \tag{53}$$

$$v_j, free \tag{54}$$

4. Case Study

In this section, we present an application of the bi-level programming model. Firstly, we conducted a case study of a subway station construction project based on real-world problems. Then, we verified the effectiveness of the proposed solution method. The experimental results were obtained by the method. Finally, we analyzed the results, and some managerial implications are provided.

4.1. Description of Subway Station Construction Project

In order to illustrate and validate the proposed bi-level programming model, we considered a case study based on real-world problems in Yantai city, Shandong Province, China. The subway stations are planned to be built. Concrete batching plants need to be selected and concrete is allocated and transported to subway stations under construction. Taking the High-Tech Industrial Development Zone as an example, there are six concrete batching plants and 14 planned stations. The locations of the candidate concrete batching plants and construction sites are presented in Figure 1.

Figure 1. Locations of the candidate concrete-batching plants and construction sites.

To conduct the test instance of the problem, detailed information is given as follows. There are three energy consumption levels of the concrete batching plants: 0.3 kgce/m^3, 0.7 kgce/m^3, and 1.1 kgce/m^3. The number of selected concrete batching plants p = 2 L/km. A concrete mixer truck of 8 cubic meters is used to transport concrete from batching plants to stations under construction. A concrete mixer truck's speed is 40 km/h with an average fuel consumption of 0.37 L/km. The demand of a station under construction is 500 shipments. The CO_2 emission factor in the production stage is EF_p = 2.6604 kg CO_2/kgce, whereas the CO_2 emission factor in the transportation stage is EF_t = 3.1212 kg CO_2/kg. The energy consumption level of the concrete batching plants is EL = [1.1, 0.7, 0.7, 0.3, 0.7, 0.3]. The distances from the candidate concrete batching plants to the construction sites are shown in Table 1.

Table 1. Distances from candidate concrete batching plants to stations (km).

	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8	Station 9	Station 10	Station 11	Station 12	Station 13	Station 14
Plant 1	5.5	5	4.8	4.7	7.3	7.1	9.3	3.4	0.88	1.1	2.2	3.8	5	6
Plant 2	5.6	5.5	5.2	4.9	7.5	7.1	9.1	3.7	1.2	1.5	2.5	3.8	5	6
Plant 3	5.9	5.7	7	3.8	6.6	6.1	7.8	3.7	1.5	0.31	1.3	3	4.2	5.2
Plant 4	8.2	8.4	6.3	5.6	4.9	3.5	3.9	7.4	4.9	3.8	2.9	2.9	2.2	3.2
Plant 5	5.6	5.8	5.3	5.2	7.3	6.8	8.6	4	1.5	1.8	2.5	3.5	4.7	5.7
Plant 6	9.5	8.2	7.4	6.6	6	4.5	3.3	7.8	5.4	4.2	3.3	3.3	2.4	2.5

4.2. Experimental Results

The case study was solved by the proposed method, which was conducted with Matlab and Gurobi on an Intel Core Quad PC with 3.3 GHz CPU and 8.00 GB RAM. The results were obtained within seconds. The optimal solution of the case is stated as follows:

$x_3 = x_4 = 1; x_1 = x_2 = x_5 = x_6 = 0; z_3 = z_4 = 3500; z_1 = z_2 = z_5 = z_6 = 0$. It is noted that Plant 3 and Plant 4 were selected for producing concrete with a supply amount of 3500 shipments. The detailed transportation plan is listed in Table 2.

Table 2. Detailed transportation plan of the case study.

	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8	Station 9	Station 10	Station 11	Station 12	Station 13	Station 14
Plant 3	500	500	0	500	0	0	0	500	500	500	500	0	0	0
Plant 4	0	0	500	0	500	500	500	0	0	0	0	500	500	500

The optimal objective value of the upper-level model was 301,348.76 kg, which is the minimum CO_2 emissions for this case. The optimal objective value of the lower-level model was 613.8750 h, which implies the minimum total transportation time.

In order to analyze the impact of the number of selected concrete batching plants and concrete demand, a series of computational experiments were conducted. Consider that the number of selected concrete batching plants was 1, 2, 3, 4, 5, 6, respectively and the demands were 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1000 shipments respectively. The results are shown in Tables 3 and 4.

Table 3. Results of different numbers of selected concrete batching plants.

	$p = 1$	$p = 2$	$p = 3$	$p = 4$	$p = 5$	$p = 6$
F1(t)	359.27	301.35	295.34	290.82	290.82	290.82
F2(h)	851.25	613.875	597.625	573.875	573.875	573.875

Table 4. Results of different demands.

	100	200	300	400	500	600	700	800	900	1000
F1(t)	60.27	120.54	180.81	241.08	301.35	361.62	421.89	482.16	542.43	602.68
F2(h)	122.775	245.55	368.325	491.1	613.875	736.65	859.425	982.2	1105.00	1227.80

4.3. Discussion

Based on the results, the following can be obtained:

(1) As seen in this model, the upper-level decision-maker (leader) should select concrete batching plants to minimize total CO_2 emissions, taking into account the lower-level decision-maker's plan. The lower-level decision-maker (follower) reacts to the leader's action, and then carries out the transportation planning depending on the leader's decision. Therefore, it is suitable to solve the low-carbon integrated problem of supplier selection and transportation by bi-level programming.

(2) From the optimal solution, it can be seen that Plant 3 and Plant 4 were selected for producing concrete. Unlike the separated model, the proposed integrated model obtained a global optimal solution. Generally speaking, the batching plant with the lowest energy consumption level should be selected in the production model by optimizing the carbon emissions, and the closest demand sites should be allocated to the facility in the transportation model by minimizing transportation time. In this model, the solution was achieved by jointly optimizing both production and transportation.

(3) According to the experimental results, we saw that the optimal objective value of the upper-level model was 301,348.76, whereas the optimal objective value of the

lower-level model was 613.8750. By implication, that is not only a game between leader and follower but also a global optimum of the problem.

(4) Table 3 and Figure 2 show that with increases in the number of selected batching plants, the total CO_2 emissions and transportation time decreased at the first stage. When the number of selected batching plants was increased to four, the total CO_2 emissions and transportation time did not decrease. This implies that it is feasible to adjust CO_2 emissions and transportation time by increasing the number of selected batching plants at first. Up to the boundary, it will not be improved.

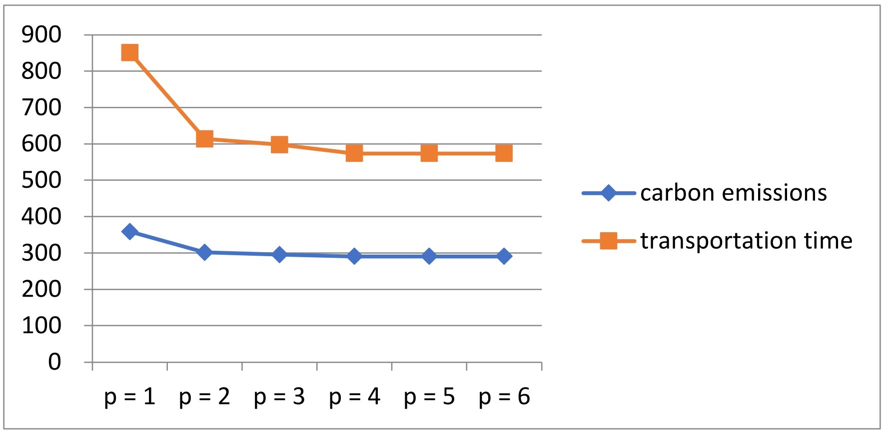

Figure 2. Impact of the number of selected concrete batching plants.

(5) As shown in Table 4, it is notable that the demands of the subway stations under construction affected the objective values directly. The total CO_2 emissions and transportation time had a linear correlation with the demands.

5. Conclusions

In order to achieve sustainable development, a low-carbon integrated problem of supplier selection and transportation planning is presented. From a low-carbon perspective, the evaluation of carbon dioxide emissions from the concrete production and concrete transportation stage are provided. From an integrated perspective, a bi-level programming model is formulated. A test instance based on real-world problems in Yantai city is conducted. According to experimental results, the proposed method achieved the optimal solution by optimizing both production and transportation. Sensitivity analysis on the number of selected concrete batching plants and demands is presented.

There are more complex constraints in real world, i.e., traffic congestion and uncertainty. For future research directions, it would be interesting to extend the integrated model with traffic congestion or uncertainty. Moreover, another future research direction is to develop more suitable algorithms for complex problems.

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