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DETERMINING THE OPTIMUM PARKING ANGLES FOR VARIOUS RECTANGULAR-SHAPED PARKING AREAS: A PARTICLE SWARM OPTIMIZATION-BASED MODEL

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Highlights

- The developed Particle Swarm Optimization-based model can increase the capacity of parking lots by up to 50% compared to fixed-parking angles.
- The optimum parking angle directly depends on the dimensions of the rectangular-shaped parking lot, which contradicts existing literature.
- The developed model can be applied to all rectangular-shaped parking lots, making it a useful tool for achieving better urban planning and reducing financial costs.

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ABSTRACT: Reducing financial costs as much as possible through the effective and efficient use of parking areas is an important issue for sustainable urban planning. This can be achieved by optimizing the placement of angles of parking-lots. In this study, to determine the optimum parking angles for rectangular-shaped parking areas, a Particle Swarm Optimization-based model that aims to maximize the capacity of parking areas is developed. In the scope of the study, firstly, 324 parking area scenarios which have different dimensions from each other are created for testing the effectiveness of the model developed. Each scenario is separately analyzed by considering the optimization-based model and fixed-parking angles (0^o, 30^o, 45^o, 60^o and 90^o) used in parking area planning. In the last step, parking area capacities obtained by applying different parking angles for each scenario and the total parking capacities for all scenarios are compared in detail. Results show that the capacities of parking areas can be increased up to approximately 50% with the model created. Besides, in contrast to existing literature, the findings of this study have proven that the optimum parking angle directly depends on the topology of the land. The model developed can be applied to all rectangular-shaped parking areas to achieve better urban planning.

Keywords: *Parking Angle, Parking-Lot, Particle Swarm Optimization, Sustainable Urban Planning*

1. INTRODUCTION

1.1. Background

People can access many things which are useful for themselves by moving from one place to another. These movements generally include different purposes such as work, education, health, travel, entertainment, shopping, etc. The factors of safety, comfort and speed have great importance in these short or long-term travels which are realized to reach the destination. While high-quality travels (safe, comfortable, and fast) make daily life much easier, low-quality travels (unsafe, uncomfortable, and slow) adversely affect road users economically and psychologically [1, 2]. The quality of urban and interurban travel is directly related to the qualifications of the transportation facilities, the integration of transportation systems with each other and/or with the environment, and the structural (physical) properties of existing transportation infrastructures. Hence, it can be said that travel quality can be significantly improved with optimally planned and appropriately designed transportation facilities, transportation systems which are integrated with each other and/or with the environment and the most properly designed transportation infrastructures.

In recent years, the population densities especially in large and medium-sized cities in developed and developing countries show an increasing trend. Therefore, these cities have been rapidly growing and continuously developing. This also triggers an increment in urban travel demands [3]. Since the distances between the origin and destination points of travel are usually long, many road users prefer motorized vehicles (private cars, public transportation vehicles) to reduce their travel times. Therefore, especially in medium and large-sized cities, the number of motorized vehicles has been rapidly increasing day by day.

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Today, the number of motorized vehicles in the world is about 1.2 billion and by the year 2035, it is expected that this number will exceed 2 billion. This also shows that the increment in the number of vehicles will continue as considerably in the course of time [4, 5]. In general, it can be thought that the increment in the number of motorized vehicles may provide big advantages such as ease of travel and simplifying daily life. But this is not an exactly correct perspective. An increment in the number of motorized vehicles brings along several problems such as traffic congestion, fatal and/or injured traffic accidents, environmental pollution and parking area insufficiencies. Indeed, it is not possible to totally overcome the aforementioned problems. However, these problems can be minimized by taking various precautions and/or by applying some structural strategies. In this context, one of the most applied strategies on highways is also the most appropriate design of transportation infrastructures. Highway transportation infrastructures consist of several components such as roads, bicycle roads, sidewalks, crosswalks, bus stops, and parking lots. While some of these components (roads, bicycle roads, and parking lots) serve the nonmotorized and/or motorized vehicles, the rest (sidewalks, crosswalks, and bus stops) serves the pedestrians. Positive impacts of appropriate designs on urban traffic are proved in many previous studies in the literature many times [6-10].

The vast majority of motorized vehicles (except for motorized vehicles which are used for transporting goods and passengers in urban and interurban) are static over most of the daily timeframe (over 90% of the day) [3]. Therefore, when the increasing number of motorized vehicles is also considered, it can be said that parking area requirements, especially in city centers, show an increasing trend. Especially in medium and large-sized cities, in case of the number of parking space are low and the capacities of the parking area are insufficient, the number of untidy parking along the roadsides also increases. This can adversely affect the continuity and regularity of traffic flows and can cause traffic congestion in certain areas. Possible problems that may occur can be minimized by increasing the number of parking lots, by appropriately designing of parking areas and by effectively using of parking areas. In brief, it can be said that urban traffic circulation can be improved by appropriately designed and optimally planned parking areas. In addition to this, in the case of the charged parking, it should be noted that parking operators may obtain more financial gains by appropriately designed and optimally planned parking areas. When all of these are considered together, it can be concluded that the parking lots have great importance in terms of urbanization, the future of cities and the economy. Hence, especially for the last 30-35 years, many scientific studies on designing, planning, and operating of parking areas have been conducted [11-18].

This study consists of four main parts. In the first part of the study, general information, background and literature review related to parking planning are given. In the second part, parking planning strategies, modeling method as well as PSO-based optimization model which is developed for optimal parking planning are explained in detail. In the third part, the scenarios created for testing the model are described. Besides, analysis results for rectangular-shaped and different-sized parking areas are comprehensively presented and the results are discussed with reference to the literature. In the last part of the study, the general findings of the study are evaluated and a possible future perspective is given.

1.2. Literature Review

In the scope of this study, since only the "planning" factor is taken into account, the studies related to "planning of parking lots" are investigated in detail. Some of these studies can be summarized as follows: Bingle et al. suggested a new method to determine optimal size and placement of parking spaces and approach corridors in a car parking lot which is sized 100′×200′ in England [19]. As a result, they pointed out that the wasted area can be minimized by using 90° parking angle instead of diagonal parking angles. Chen et al. studied on the determination of optimum parking angle in the large parking lots. At the end of some field studies and mathematical analysis, they stated that the capacities of parking lots can be maximized by using 70° parking angle. Besides, in the scope of the study, the planning with 70° parking angle was compared with the planning with 90° parking angle. They concluded that the planning with 70° parking angle is more appropriate than the planning with 90° parking angle in terms of parking maneuvers and traffic safety [20]. Iranpour and Tung developed a new method to maximize the capacities of parking lots. It was stated that the parking maneuvers can be made safer and the capacities of parking lot can be increased by applying different parking angles at different regions in a parking area [21]. Brown-West proposed an optimization model for planning and designing of parking lots at campus environments. The effective use of campus lands was aimed with the proposed model. In the scope of the study, various helpful (critical) suggestions were presented to campus planner and university administrators for the planning of the parking lots [22]. Munzir et al., in their study, used linear integer programming method for optimizing the parking lots. The optimization model was created using survey and observation data [23]. As a result, it was indicated that a new user requirement based model for parking space optimization was developed. Robert and Drago focused on the applicability of information technologies which are used for the optimization of parking spaces. Obtained results showed that effective use of capacity in parking areas can be achieved with applied different technologies [24]. Abdullah et al. developed a new mathematical model to maximize the capacity of the parking area which is limited to a certain land. In the scope of the study, three different parking plannings were taken into consideration and then they were compared with each other. As a result, it was pointed out that the capacities of parking areas can be increased by using the model developed [25]. Guo and Guo suggested a new method which considers automatic planning and manual adjustments together for the planning of parking lots in the parking areas. Then, the effectiveness of the suggested method was proved in a sample study [26]. Wang and Yuan, in their study, presented several planning suggestions related to parking lots and parking garages to decision-makers and planners [27]. Abdelfatah and Taha studied on the determination of the optimum angles of parking lots. They used a linear integer programming method for determining the optimum parking angles. In the analyses carried out for three different parking areas, the effects of different parking angles on the capacities of parking areas were determined [28]. Zhao et al. developed a new parking planning method for smart parking systems. In the scope of the study, the parking planning problem was transformed into a kind of linear assignment problem. As a result, it was seen that effective and successful results can be obtained by using the developed model in the planning of the parking lots [29]. Oladejo and Awuley used a linear programming method for the optimization of the parking spaces. At the end of the study, it was pointed out that the user satisfaction level can decrease due to the limited maneuvering area when the parking capacity in a certain area increases [30]. Ramli et al. developed a new approach which maximizes the number of parking lots in a parking area considering different parking angles. In the research, it was determined that parking revenues can be increased over 15% with this new approach [31]. Yang and Huang focused on existing problems related to urban parking planning. Besides, they discussed measures (precautions) which should be applied in order to prevent possible problems. In the scope of the study, the importance of parking lots planning was emphasized [32]. Ramli et al. studied on a new mathematical model for the optimization of triangular-shaped parking lots. They aimed the maximization of the parking capacities by using linear integer programming. Consequently, it was specified that the developed model is an effective and applicable model under certain conditions [33]. Shayrini et al. developed a new model for planning of parking lots in triangular-shaped parking areas. In the research, a linear integer programming method was used to determine the maximum number of parking lots in a certain area. In the scope of the study, obtained results for isosceles and equilateral triangular-shaped parking areas were evaluated and interpreted, separately [34]. Putri et al. studied on the optimization of parking spaces in parallelogram-shaped and right triangle-shaped parking areas. They developed different mathematical models for both type of parking areas. As a result, it was seen that developed models are utilizable and applicable for parking planning [35]. Dianawati and Kristianto focused on the planning of parking lots in a recreational area. In the study, linear integer programming method was used for determining the optimum parking angle and the number of parking lots. As a result, it was specified that parking revenues can be increased and the comfort of recreational area can be improved by using the model suggested [36]. Hasbiyati et al. aimed to optimize parking lots in parallelogram-shaped parking areas considering rectangle and right triangle concept, separately. Obtained results showed that the parking angle of 90^{o} is the most appropriate parking angle for parallelogram shaped parking areas [37]. Yildirim et al. used the cutting-stock formulation for the planning of a rectangular-shaped university campus parking area. In the study, they aimed to maximize the capacities of stated parking area. At the end of the study, it was seen that the parking capacity can be increased about 15% by using the proposed approach [38].

When the previous studies are investigated carefully, it can be seen that the parking spaces in the parking lots were planned considering constant parking angles (0°, 30°, 45°, 60° and 90°) generally. Similar methods were used in the optimization process in most of these studies. In this study, as a differ from the literature, parking lots in parking areas were optimized considering all angle values between 0° and 90°. In addition, meta-heuristic Particle Swarm Optimization (PSO) algorithm which provides fairly good results in solving of the many engineering problems was preferred as solution method instead of conventional methods.

2. MATERIAL AND METHODS

2.1. Planning of Parking Lots

In urban planning, one of the most important land-use patterns is also parking lot. Since the activities and mobilities are intense at the regions such as stadiums, airports, terminals, shopping malls, residential areas, and business centers, higher capacity parking areas are needed at these regions (Table 1) [39]. This situation causes an increment in land use in the specified regions and brings about additional land costs. Well-planned parking lots are seen as an important step to minimize stated negations.

Table 1. Average parking spaces requirements for some regions

The Type of Confined Area	For each 100 m² of Confined Area	
	Average	Limit Values
Bank	5.4	1.8 – 10.8
Terminal	4.8	1.7 – 7.9
Hospital	3.8	1.1 – 8.6
Government Agency	3.6	1.2 – 6.0
Shopping Mall	2.8	1.4 – 5.1
Restaurant	2.1	0.9 – 3.3
Commercial Building	1.5	0.4 – 2.9
Hotel	0.6	0.4 – 1.0

Parking are classified as roadside parking and off-street parking in generally. In the roadside parking lots, users can park their vehicles on the roadsides or parking bays for limited duration or indefinitely. In these type of parking lots, a part of the road is occupied in most of the time. Therefore, traffic congestion can be seen at these areas. Roadside parking lots can be planned considering different parking angles (0°, 30°, 45°, 60° and 90°) [40, 41]. Dimensions of parking spaces for each parking angle are shown in Figure 1 in detail [39].

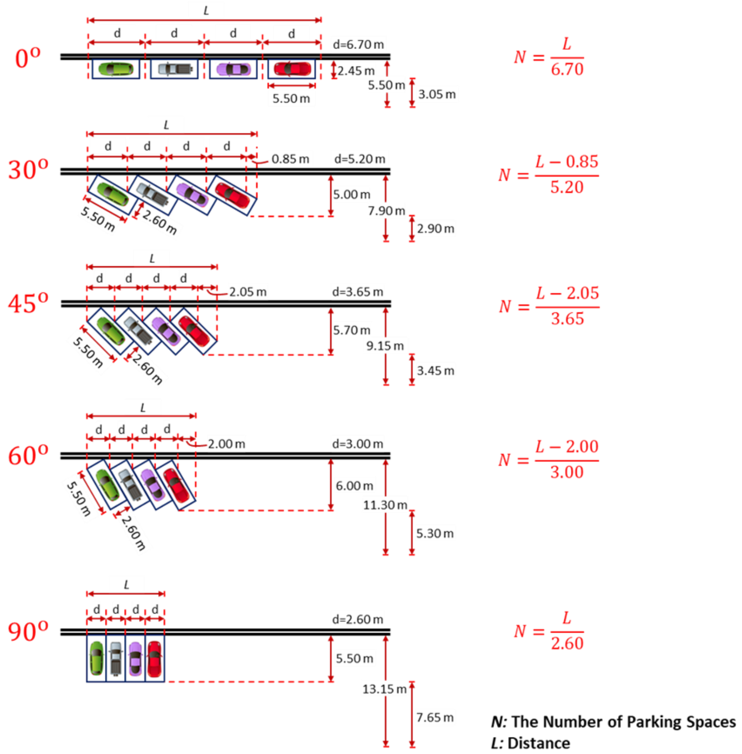
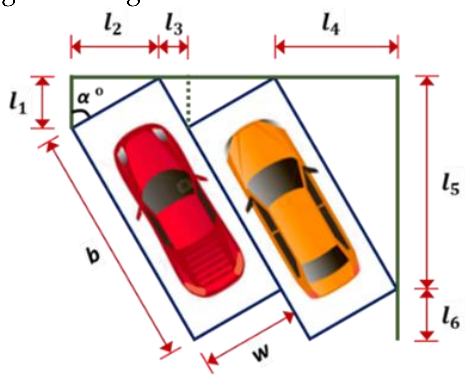


Figure 1. Dimensions of roadside parking spaces for each parking angle [39]

As can be seen from the Figure 1, when the parking angle increases, both the parking capacity and the width of corridor increase. According to this, it is thought that ensuring the balance of parking capacity and land use is quite important issue in parking planning. The calculations of lengths of occupied area in the angled parking planning are given in Figure 2.



b = Length of the parking space

w = Width of the parking space

α^o = Parking angle

$l_1 = w * cos(\alpha^o)$; $l_2 = w * sin(\alpha^o)$

$l_3 = x_1 * cot(\alpha^o)$; $l_4 = b * cos(\alpha^o)$

$l_5 = b * sin(\alpha^o)$; $l_6 = w * cos(\alpha^o)$

Figure 2. The calculations of lengths of occupied area in the angled parking planning

Off-street parking spaces (parking lots and parking garages) are the specific areas where users can park their vehicles for a long duration. In these type of parking areas, there is no continuous interaction with urban traffic flows. Therefore, it can be said that off-street parking lots are safer than roadside parking lots. In off-street parking lots, planning strategies like roadside parking lots are applied. In the planning stage, the same values of parking space dimensions and the corridor widths can be used [39, 42, 43].

Two-row parking plans for commonly used different parking angles are depicted in Figure 3. As can be seen from Figure 3, the corridor widths for 0°, 30°, 45°, 60° and 90° are calculated as 3.05, 2.90, 3.45, 5.30 and 7.65, respectively. Besides, when the angle of parking lots increases, the width of parking area decreases and length of parking area increases.

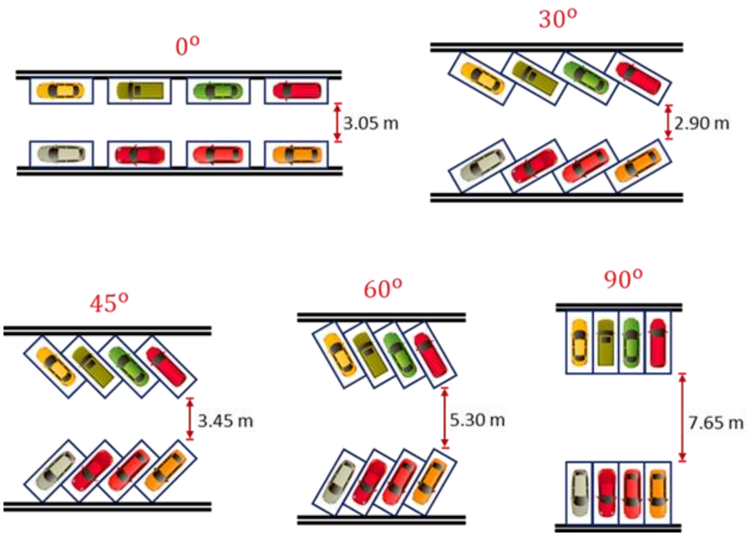


Figure 3. Two-row parking plans for different parking angle

In a parking area, corridor widths directly depend on parking angle as shown in Figure 3. The findings demonstrate that there is not a significant change in corridor widths with the increment of parking angle from 0° to 30°. However, as shown in Figure 4, the for higher parking angle values than 30° the corridor widths remarkably increases.

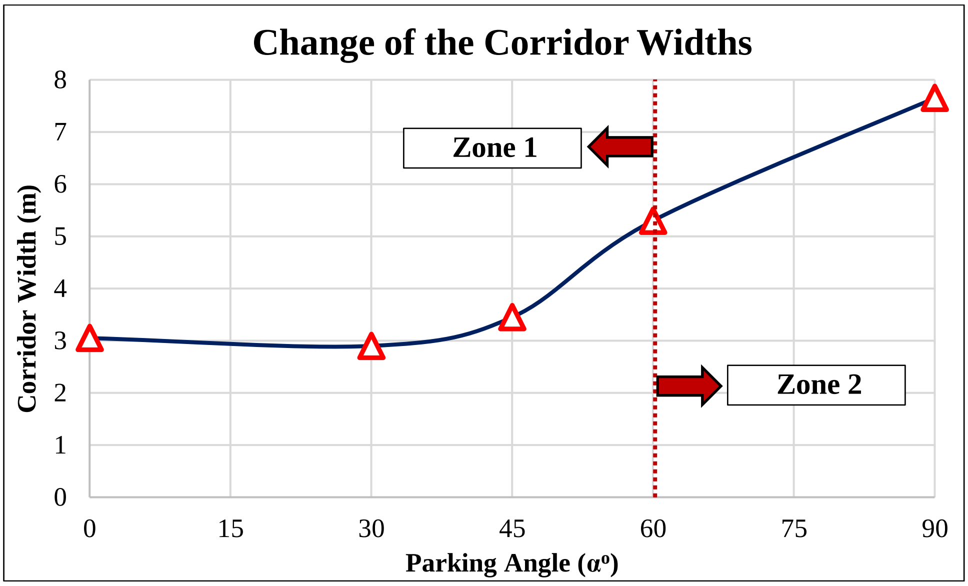


Figure 4. The change of corridor widths depending on the parking angles

As it has been mentioned before, the optimization of parking angles is aimed in the scope of this study. Thus, by using the most appropriate corridor widths for the most used angle values (0°,30°, 45°, 60 ° and

90°) in the literature [11, 40, 41], a generalized model for representing all angle values between 0° and 90° and have to be formulated. When the Figure 4 is examined carefully, in case of parking angle is between 0° and 60° it is seen that corridor widths increase in a polynomial way (Zone 1). Since, there is not any data in the literature representing the relationship between the parking angle and the corridor width for any angle value in the range of 60° and 90°, it is assumed that the corridor widths increase as linearly (Zone 2). This assumption is also verified for interpolated values with trigonometric calculations. Therefore, these two zones (Zone 1 and Zone 2) are handled separately in the modelling stage of the corridor widths. For both zones, obtained results from the modelling which made by applying the curve fitting approach are presented in Figure 5 in details.

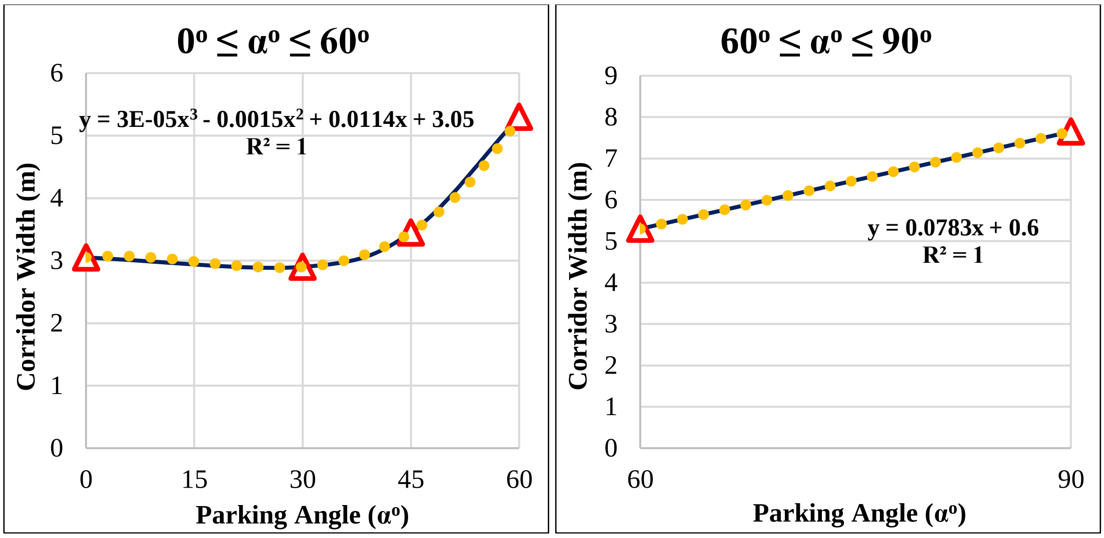


Figure 5. Corridor width modelling depending on the parking angles for both zones

In Figure 5, when the obtained determination coefficient values (R^2) for both zones are investigated carefully, it is seen that these values equal to 1. This shows that the variance of dependent variable (corridor width) can be explained by independent variable (parking angle) at high levels. According to this, it can be said that the reliability levels of obtained relations (corridor width-parking angle) are quite high.

In case of parking angle (α) is between 0° and 60°, corridor width can be calculated by Equation 1:

$$CW = 0.00003272 \times (\alpha)^3 - 0.0015278 \times (\alpha)^2 + 0.011389 \times (\alpha) + 3.05 \quad (1)$$

In case of parking angle (α) is between 60° and 90°, corridor width can be calculated by Equation 2:

$$CW = 0.0783 \times (\alpha) + 0.60 \quad (2)$$

where;

CW = Corridor widths in meters,

α = Parking angle in degrees.

2.2. Modeling

In this part of the study, the maximum number of vehicle (F) in a rectangular-shaped parking areas is parametrically defined as a function of the dimensions of the parking lot as follows (Equation 3):

$$F = N_1 \times N_2 \quad (3)$$

where N_1 and N_2 are the number of vehicles that fit to L_1(width of the parking area) and L_2 (length of the parking area), respectively.

Here, N_1 and N_2 are determined according to the following equations (Equation 4-20):

$*\ \boldsymbol{for\ N_1;}$

- **If** $\alpha = 0°$;

$N_1 = fix\left(\frac{L_1}{6.7}\right)$ .... (4)

- **Elseif** $0° < \alpha \le 90°$

$N_1 = fix\left(\left(L_1 - 5.5 \times \cos(\alpha) + \frac{2.6\times\cos^2(\alpha)}{\sin(\alpha)}\right) / \left(2.6 \times \sin(\alpha) + \frac{2.6\times\cos^2(\alpha)}{\sin(\alpha)}\right)\right)$ .... (5)

$*\ \boldsymbol{for\ N_2;}$

- **If** $\alpha = 0°$;

$s = fix\left(\frac{L_2}{7.95}\right)$ .... (6)

$n = s \times 7.95$ .... (7)

$t = L_2 - n$ .... (8)

here s and n are the net number of two-row parking and total length used for two-row parking, respectively. Besides, t is residual length in case of two-row parking.

If $t \ge 5.5$

$N_2 = 2 \times s + 1$ .... (9)

else

$N_2 = 2 \times s$ .... (10)

- **If** $60° > \alpha > 0°$

$s = fix\left(\frac{L_2}{5.5\times\sin(\alpha)} + 2.6 \times \cos(\alpha) + CW\right)$ .... (11)

$n = s \times (CW + (2 \times (5.5 \times \sin(\alpha) + 2.6 \times \cos(\alpha))))$ .... (12)

$t = L_2 - n$ .... (13)

If $t \ge (5.5 \times \sin(\alpha) + 2.6 \times \cos(\alpha) + CW)$;

$N_2 = 2 \times s + 1$ .... (14)

else

$N_2 = 2 \times s$ .... (15)

- **If** $90° \ge \alpha \ge 60°$

$s = fix\left(\frac{L_2}{5.5\times\sin(\alpha)} + 2.6 \times \cos(\alpha) + CW\right)$ .... (16)

$n = s \times (CW + (2 \times (5.5 \times \sin(\alpha) + 2.6 \times \cos(\alpha))))$ .... (17)

$t = L_2 - n$ .... (18)

If $t \ge (5.5 \times \sin(\alpha) + 2.6 \times \cos(\alpha) + CW)$;

$N_2 = 2 \times s + 1$ .... (19)

else

$N_2 = 2 \times s$ .... (20)

2.3. Optimization

Particle Swarm Optimization (PSO) is a nature-inspired stochastic method which is based on mimicking the social learning behavior of birds and fishes [44, 45]. This algorithm has been of interest to scientists searching for optimum parameters for various engineering areas including biomechanics [46], food engineering [47], traffic and transportation engineering [48], etc. In this algorithm, each particle, representing a member of the swarm population, is considered as a feasible solution for the optimization problem. In PSO technique, each particle is characterized by different parameters representing the position (x_i) and velocity (v_i) of the i'th particle in D-dimensional vectors and are expressed as:

$x_i = (x_{i1}, x_{i2}, \dots, x_{iD})$ .... (21)

$v_i = (v_{i1}, v_{i2}, \dots, v_{iD})$ .... (22)

In each iteration, the position and velocity values of the particles are updated according to the following equations:

$x_i(t+1) = x_i(t) + v_i(t+1)$ .... (23)

$v_i(t+1) = wv_i(t) + R_1c_1(P_i - x_i(t)) + R_2c_2\left(P_g - x_i(t)\right)$.. (24)

where w represents the inertia coefficient, R_1 and R_2 stand for two distinct, randomly selected values between 0 and 1, c_1 and c_2 represent the individual and social acceleration parameters respectively; P_i denotes the particle's best individual position encountered so far, and P_g signifies the best position among all individuals in the swarm. In this study, PSO is simply implemented to parking lot planning problem as follows:

$$\max F_{cap} = f(x_1)$$
$$s.t.$$
$$90 \geq x_1 \geq 0$$

where F_{cap} and x_1 denote maximum parking area capacity and parking angle, respectively. To decrease the computational expense and to increase the efficiency of the codes, the master program is linked to 2 slave subroutines. Master program basicly includes 4 main steps which are problem definition, defining PSO parameters, calling 1st slave subroutine and storing the results, respectively. In the problem definition section, the optimization problem is defined and connected to the 1_{st} slave subroutine in order to iteratively get the fitness value of each particle. In the 2_{nd} main step, PSO parameters are defined. Individual and social acceleration coefficients (c_1 and c_2) are set as 2.00 for both parameters. The inertia coefficient (w), the most dominant parameter on convergence characteristics of the algorithm, is defined as linearly decreased in each iteration from the value of 1.00 with a damping coefficient of 0.99. The maximum number of iterations and population size are selected as 100 and 10, respectively. The 3rd section involves calling 2_{nd} slave subroutine. This subroutine initiates the swarm population members by generating a random position and velocity for each particle. After assignment of the initial values of the swarm members, the main iterative loop is run in order to reach the possible global best value. The fitness values evaluated for each particle are stored and compared with its previous ones in order to iteratively update the personal best (P_{best}). The global best value is obtained by comparing the P_{best} with the global best (G_{best}) in each iteration. Once the stopping criteria is satisfied, the process terminates and the optimum value is obtained. The last step of the main program is storing the best results obtained and plotting the convergence curve of the process. The outline of the optimization process conducted in this study is given in Figure 6.

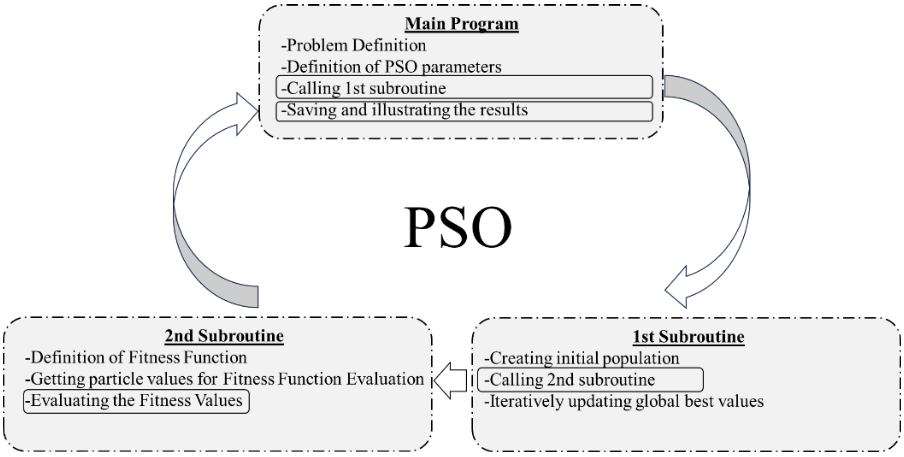


Figure 6. The flowchart of the MATLAB optimization process

Using the aforementioned method, the best parking angles in terms of maximum vehicle capacity are separately determined for various rectangular-shaped parking lot cases and are presented in the following section in detail.

3. RESULTS AND DISCUSSION

In this part of the study, it is aimed to test the performance of the developed optimization model for different rectangular-shaped parking areas. For this reason, firstly, four different land types are considered for parking scenarios. The minimum parking area is determined by multiplying the minimum width by the minimum length, while the maximum parking area is determined by multiplying the maximum width by the maximum length. Both edges are increased from by 10 meter until the maximum value and 81 sample cases (9*9=81) are created for each land type. Information related to each land type is given in Table 2.

Table 2. Topology of the Land Types

Land Type I (width x length) (m x m)	Land Type II (width x length) (m x m)	Land Type III (width x length) (m x m)	Land Type IV (width x length) (m x m)
15 x 15	20 x 15	15 x 20	20 x 20
15 x 25	20 x 25	15 x 30	20 x 30
…	…	…	…
15 x 95	20 x 95	15 x 100	20 x 100
25 x 15	30 x 15	25 x 20	30 x 20
25 x 25	30 x 25	25 x 30	30 x 30
…	…	…	…
25 x 95	30 x 95	25 x 100	30 x 100
…			
95 x 15	100 x 15	95 x 20	100 x 20
95 x 25	100 x 25	95 x 30	100 x 30
…	…	…	…
95 x 95	100 x 95	95 x 100	100 x 100

Since each land type has 81 sample cases, 324 different parking scenarios were created. The upper and lower limits of the parking lots are defined as 225 m^2 (15 m*15 m) and 10000 m^2 (100 m*100 m), respectively. Dimensions of the parking lots for randomly selected scenarios are presented in detail in Table 3.

Table 3. Parking dimensions for different land types

No	Land Type I		Land Area (m²)	No	Land Type III		Land Area (m²)
	Width (m)	Length (m)			Width (m)	Length (m)	
1	15	15	225	**170**	85	20	1700
6	65	15	975	**176**	55	30	1650
14	55	25	1375	**184**	45	40	1800
26	85	35	2975	**192**	35	50	1750
33	65	45	2925	**207**	95	60	5700
41	55	55	3025	**216**	95	70	6650
58	45	75	3375	**225**	95	80	7600
64	15	85	1275	**231**	65	90	5850
75	35	95	3325	**238**	45	100	4500
81	95	95	9025	**243**	95	100	9500
No	**Land Type II**		**Land Area (m²)**	**No**	**Land Type IV**		**Land Area (m²)**
	Width (m)	**Length (m)**			**Width (m)**	**Length (m)**	
86	60	15	900	**250**	80	20	1600
98	90	25	2250	**261**	100	30	3000
105	70	35	2450	**268**	80	40	3200
119	30	55	1650	**276**	70	50	3500
124	80	55	4400	**287**	90	60	5400
131	60	65	3900	**294**	70	70	4900
140	60	75	4500	**300**	40	80	3200
149	60	85	5100	**311**	60	90	5400
157	50	95	4750	**322**	80	100	8000
162	100	95	9500	**324**	100	100	10000

In the second stage, parking capacities have been determined for each scenario in case of different parking angles (0^o, 30^o, 45^o, 60^o and 90^o) are applied. Thereafter, using the PSO-based optimization algorithm, optimum parking angles and the corresponding vehicle capacities have been determined for each scenario. Subsequently, the results have been comparatively evaluated and some of the comparisons have been shown in Table 4. The maximum parking capacity obtained for each scenario has been marked in green color.

As seen in Table 4, the proposed method based on PSO has provided promising results in terms of parking lot planning. When all the obtained results were carefully examined, it was determined that parking capacities could be increased up to 25% with the optimization-based approach conducted in this study. The scenarios with the highest capacity increment rates for four different land types considered within the scope of the study are detailly presented in Table 5.

Table 4. Parking capacity results for some sample scenarios

No	Land Type	Width (m)	Length (m)	Land Area (m²)	Optimum Parking Angle Determined(°)	Parking Capacity (veh)					
						0°	30°	45°	60°	90°	This study
7	I	75	15	1125	45.62	33	28	38	24	28	**40**
21	I	35	35	1225	60.33	40	30	36	**44**	39	**44**
35	I	85	45	3825	57.83	120	96	132	108	128	**135**
42	I	65	55	3575	72.09	117	96	119	126	125	**138**
54	I	95	65	6175	52.22	**224**	180	200	217	216	**224**
66	I	35	85	2975	69.90	105	72	99	99	104	**108**
71	I	85	85	7225	69.73	252	192	242	243	256	**270**
80	I	85	95	8075	86.87	276	224	264	270	**320**	**320**
91	II	20	25	500	47.94	12	9	12	12	14	**15**
97	II	80	25	2000	47.55	**66**	45	63	52	60	**66**
114	II	70	45	3150	57.67	100	78	108	88	104	**110**
116	II	90	45	4050	45.42	130	102	**144**	116	136	**144**
126	II	100	55	5500	72.12	182	152	182	192	190	**216**
132	II	70	65	4550	53.59	160	130	144	154	156	**168**
150	II	90	85	7650	70.21	273	204	264	261	272	**288**
160	II	80	95	7600	83.34	253	210	252	260	**300**	**300**
175	III	45	30	1350	65.45	42	32	44	42	34	**45**
178	III	75	30	2250	45.65	77	56	76	72	56	**80**
192	III	35	50	1750	70.79	**60**	42	54	55	52	**60**
194	III	55	50	2750	77.64	96	70	84	85	84	**100**
198	III	95	50	4750	77.36	168	126	150	155	144	**175**
211	III	45	70	3150	88.50	102	80	99	112	**119**	**119**
233	III	85	90	7650	65.84	264	208	264	270	288	**290**
241	III	75	100	7500	79.72	264	210	247	264	**280**	**280**
254	IV	30	30	900	67.48	28	20	28	27	22	**30**
260	IV	90	30	2700	45.37	91	68	**96**	87	68	**96**
268	IV	80	40	3200	80.62	110	90	105	104	**120**	**120**
272	IV	30	50	1500	79.58	48	35	42	45	44	**55**
279	IV	100	50	5000	55.86	168	133	156	160	152	**186**
295	IV	80	70	5600	80.94	187	150	189	208	**210**	**210**
308	IV	30	90	2700	66.88	88	65	84	90	99	**100**
314	IV	90	90	8100	66.46	286	221	288	290	306	**310**

Table 5. The scenarios with the highest capacity increment rates for four different land types

No	Land Type	Width (m)	Length (m)	Optimum Parking Angle Determined (°)	Parking Capacity (veh)						Improvement Rates (%)
					0°	30°	45°	60°	90°	This study	
43	I	75	55	72.54	143	112	133	**144**	140	**162**	**12.50**
123	II	70	55	71.96	130	104	126	**132**	130	**150**	**13.64**
191	III	25	50	79.84	**36**	28	**36**	35	**36**	**45**	**25.00**
273	IV	40	50	55.43	**60**	49	**60**	**60**	**60**	**72**	**20.00**

In the next stage of the study, the total parking capacities for all land types have been separately determined in case of applying different parking angles for the created parking scenarios. Thereafter, the obtained total parking capacity values were compared with each other by considering the parking angles. The hierarchical structure created for comparisons is shown in Figure 7.

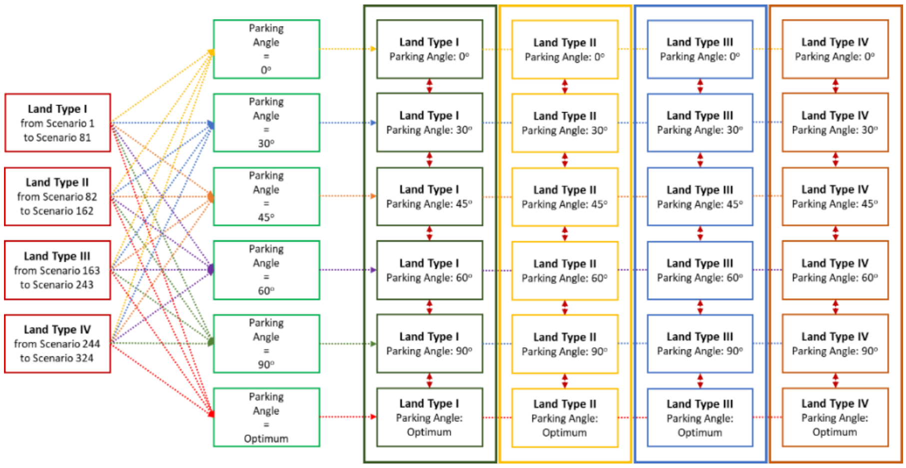


Figure 7. Hierarchical structure created for the comparison of total parking capacities

As can be seen from Figure 7, total capacity comparisons have been made for each land type. For four different land types, the total parking capacities obtained from the analyzes conducted considering different parking angles have graphically presented in Figure 8.

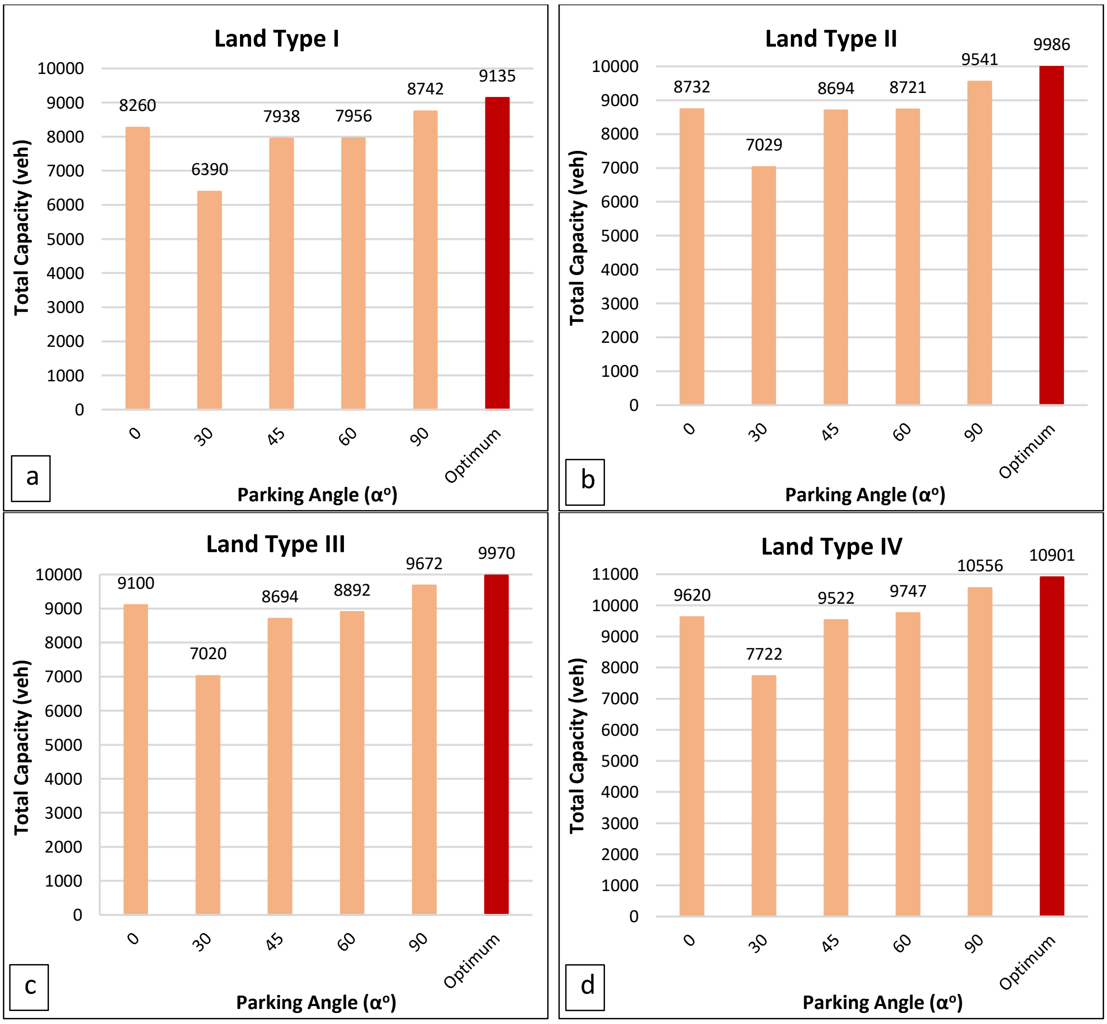


Figure 8. Total parking capacity reached in case of different parking angles are applied for four different land types: (a)Land Type I, (b)Land Type II, (c)Land Type III and (d)Land Type IV

From Figure 8, it can be seen that the highest total parking capacity values for all land types are obtained using the optimization-based approach developed within the scope of this study. Total capacities are determined as 9135, 9986, 9970 and 10901 vehicles for land types I to IV, respectively. Additionally, it has been concluded that the lowest total capacity values are also obtained when the parking angle is 30°. If the parking angle is equal to 90°, the results are closer to the total vehicle capacities obtained by applying the optimum parking angle for parking lot planning.

It has been found that if the parking angles are designed as 0°, 45° and 60°, similar capacity values are obtained. However, it has been determined that these values are lower than the total capacity values obtained when the parking angle is designed as 90°. When Figure 8 is carefully examined, it can be said that the total parking area capacities can be increased by applying the optimum parking angle approach. In the case of optimum parking angle application, the capacity increment rates obtained for each land type compared to fixed parking angle applications are shown in detail in Figure 9.

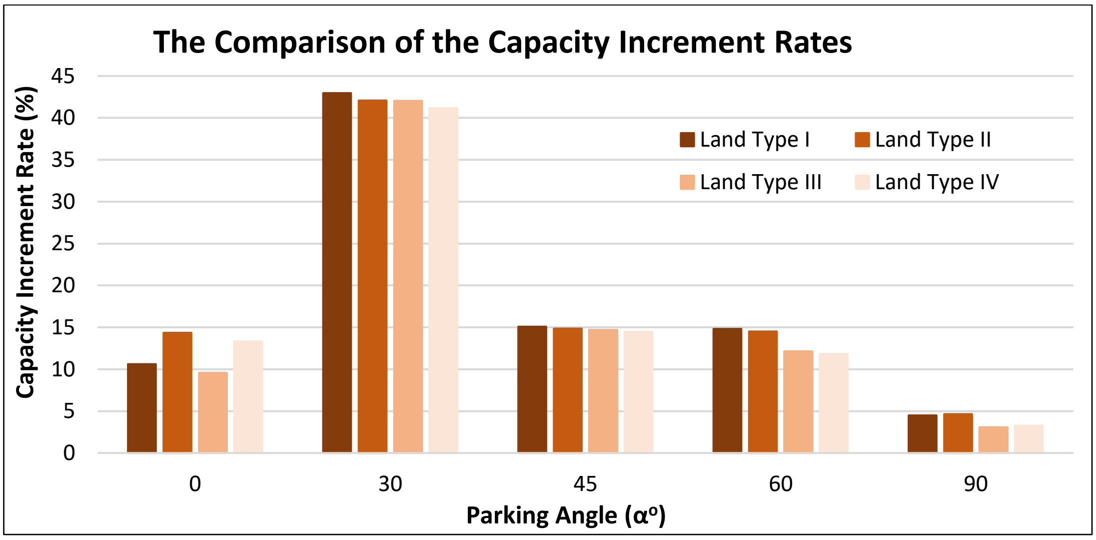


Figure 9. Capacity increment rates compared to fixed parking angle applications in the case of optimum parking angle application

As can be seen from Figure 9, the lowest and highest capacity increments are obtained when the parking angle is applied as 90° and 30°, respectively. If the parking angle is equal to 90°, the capacity increment rates are between 3% and 5%, whereas if the parking angle is equal to 30°, the increase rates range from about 41% to 43%. If the parking angles are equal to 0°, 45° or 60°, the increments in total parking capacities are approximately in the range of 10% to 15%. In addition, when Figure 9 is examined carefully, it can be seen that there is no significant difference in capacity increment rates for the same parking angle values in four different land types.

In this part of the study, for four different land types, the number and percentages of the scenarios whose capacities that can be increased by applying the optimum parking angle instead of fixed parking angles have been determined. At this stage, the obtained results have been evaluated by considering the parking angles and the land types separately. For each land type, instead of fixed parking angles, the scenario numbers and percentages, whose capacities can be increased if the optimum parking angle is applied, are graphically shown in Figure 10.

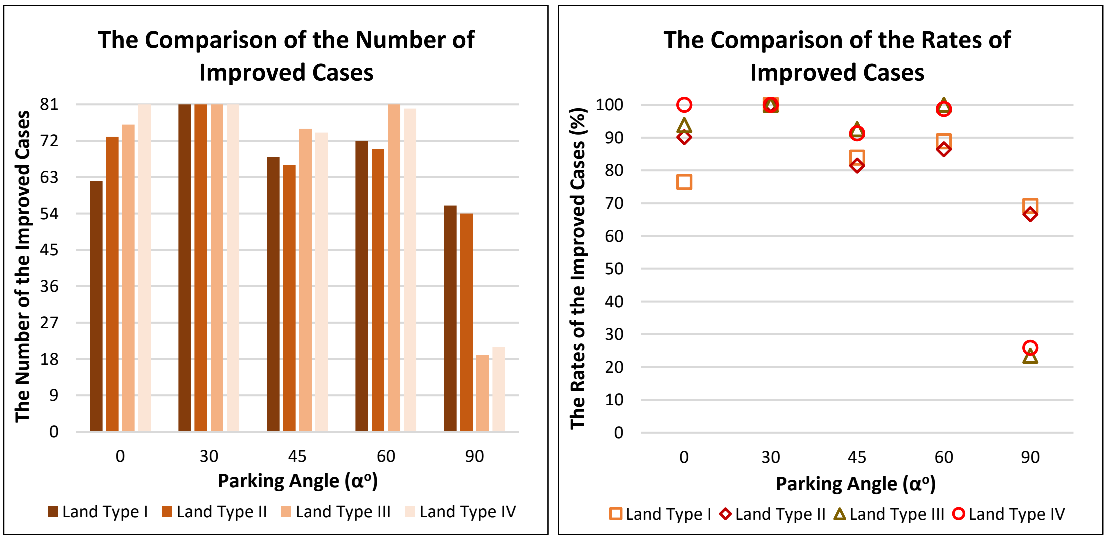


Figure 10. The number and percentages of the improved scenarios if optimum parking angle is applied instead of fixed parking angles

From Figure 10, it can be seen that in all land types, parking capacities can be increased for all scenarios if the optimum parking angle is applied instead of 30^{o} parking angle (worst parking angle for created cases). In the case of 30º parking position, since the vehicles are parked close to horizontal, the the horizontal occupancy of the parcel increases. In addition, the vertical occupancy also increases due to higher values of corridor widths. In such cases, it is expected that the parking capacity decreases. In the literature, there are several studies considering the parking angles of 0°,30°,45°,60° and 90°. However, none of these studies suggest 30° parking position due to decrease in total capacity [28, 31, 36]. The results of the current study also verify this information (Figure 8-10). If the optimum parking angle is applied instead of a 90^{o} parking angle, it can be said that the parking capacity can be increased in approximately 70% of the scenarios for Land Type I-II and approximately 25% of the scenarios for Land Type III-IV. Additionally, in all land types, it is seen that the scenario rate, whose capacity can be increased even if the optimum parking angle is applied instead of parking angles of 0^{o} - 45^{o} or 60^{o}, varies between 75% and 100%.

In previous studies, parking lots are generally located considering the fixed parking angles [11, 40, 41]. However, the results of the current study demonstrate that optimizing the parking angles depending on the topology of the parking area has a crucial importance in terms of increasing the parking capacities. Moreover, one can find contradictory results in the literature in terms of determining the optimum parking angle. While some researchers claim that the best parking angle is 90^{o} [19, 37], others argue that it is 70^{o} [20]. However, the findings of this study have proven that the optimum parking angle, which provides maximum parking capacity, directly depends on the dimensions of the parking area (width and length). Therefore, a specific approach should be applied for each parking area and a universal optimum angle can not be offered as done in the aforementioned studies. By using the optimization-based approach, it has been determined that the capacities of the rectangular-shaped car parking areas can be increased up to 25%.

4. CONCLUSIONS

In this study, it is aimed to optimally plan the rectangular-shaped car parking lots. In this context, a new model based on parking angle optimization has been developed in MATLAB using the Particle Swarm Optimization (PSO) algorithm. The effectiveness of the developed model has been tested on 324 scenarios which have different sizes of car parking areas considering the parking capacity criteria. According to the results of all scenarios considered within the scope of the study, total capacity increment rates obtained using the optimum parking angle approach are as follows:

- Approximately 41% to 43%, compared to 30^{o} fixed parking angle;
- Between 10% and 15%, in comparison with the fixed parking angles of 0^{o}, 45^{o} or 60^{o};
- Between 3% and 5%, compared to the fixed parking angle of 90^{o}.

As stated earlier, in this study, the maximum parking area is limited to 10000 m^2.

If the maximum parking area is limited to 5000 m^2 using the same parking area examples; total capacity increment rates are as follows:

- Approximately 43% to 47%, compared to 30^{o} fixed parking angle;
- Between 11% and 17%, in comparison with the fixed parking angles of 0^{o}, 45^{o} or 60^{o};
- Between 5.5% and 6.5%, compared to the fixed parking angle of 90^{o}.

According to these results, it can be concluded that if the maximum parking area is decreased, total capacity increment rates are increased. In all land types considered within the scope of the study, it was concluded that the scenario rate, whose capacity can be increased if the optimum parking angle is applied instead of fixed parking angles, varies between approximately 25% and 100%.

In summary, it can be stated that, with the developed optimization-based approach, the parking lots can be optimally planned in order to efficiently use the parking areas as much as possible. It is thought that the developed approach may also provide an opportunity to reduce the high budgets allocated for parking areas. As mentioned earlier, this study covers only the planning of rectangular-shaped parking lots. In future studies, it is aimed to consider different land topologies (trapezoidal, triangular, etc.) and to develop new planning models for these land types.

Declaration of Ethical Standards

Authors declare to comply with all ethical guidelines, including authorship, citation, data reporting, and original research publication.

Credit Authorship Contribution Statement

Z. CAKICI: Methodology, Conceptualization, Resources, Investigation, Writing - review & editing, Supervision.

A. T. ŞENSOY: Methodology, Conceptualization, Resources, Investigation, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The dataset generated during the current study are available from the corresponding author on reasonable request.

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