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Design of a Rectangular Parking Lot Using a Cutting-Stock Formulation

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Abstract: Ever-increasing number of vehicles on the roads and in need of parking facilities at a site creates a constant burden for drivers trying to find a parking space and obstructs maneuvering both in parking areas and also along the roadways on which cars are, sometimes arbitrarily, parked. These problems are aggravated for sites built long time ago when demand for parking used to be much less than it is now. The available space may be limited because of the buildings, green areas, etc., surrounding the parking spaces and the site, and construction of a multi-story garage may not be an option in some cases due to regulations and/or financial reasons. We use a cutting-stock formulation to redesign parking lots that are rectangular in shape but with various dimensions in order to maximize the number of parking stalls. Spreadsheets are used to facilitate pattern generation and Excel Solver add-in is used to solve the optimization model for a set of selected parking lots at a university campus and we obtained improvements up to 22% more parking stalls per lot.

Keywords: Cutting-stock model, optimization, parking, pattern generation.

1. Introduction and Literature Review

Vehicles sold or registered continue to increase both in Turkey and also abroad, requiring authorities to take actions to meet parking demands of users. Figure 1 shows the quantities of passenger cars sold (or registered) and those estimated to be still in use in Turkey since 2008.

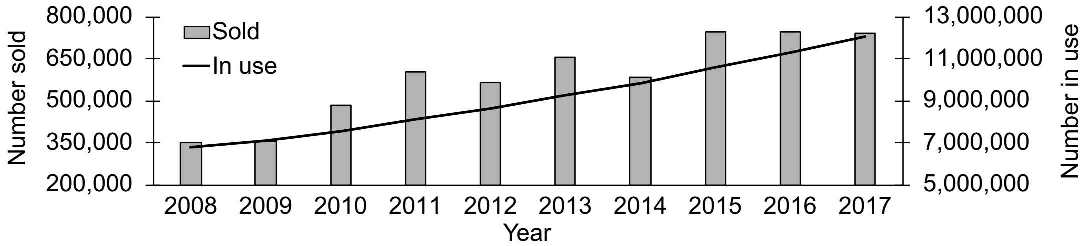

FIGURE 1. Passenger cars sold (or registered) and estimated to be in use in Turkey since 2008. (Data Source: European Commission, Eurostat, URL: https://ec.europa.eu/eurostat/web/transport/data/database)

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For sites built quite a while ago, providing additional spaces to meet the increasing parking demand may be a complicated and costly problem if the available space is limited. Building a multi-story parking garage will require a large investment and may interrupt the other activities of the site, and sometimes even if the required financing is available, regulations may prevent building new structures for some sites. When such is the case, an alternative approach could be to redesign the existing parking areas and other available spaces. In particular, this study considers redesigning parking lots for a site that are rectangular in shape with varying dimensions. A parking lot is defined as surface on grade open to sky and is an off-street parking facility, i.e., one located on site. Our objective is to redesign existing, albeit insufficient, parking lots to increase number of parking stalls without a major overhaul.

Designing parking spaces requires joint consideration of (1) design and regulatory requirements and guidelines, (2) space and location limitations of the site, (3) demands and needs of the users who include both the drivers and also the pedestrians, and (4) total costs of owning and operating the parking facilities.

Minimum design requirements are determined by appropriate bodies of the government and municipal authority via regulatory laws and ordinances, and are usually summarized in directives and traffic engineering handbooks. The design requirements include, but are not limited to, minimum quantities of parking spaces required per square footage of the facility, portion of those parking spaces that should be reserved as accessible spaces and for different types of vehicles such as motorcycles and bicycles; allowable types of parking facilities, geometry and dimensions safe for parking and maneuvering, etc. [5]. Specific outlines and ordinances pertaining to parking spaces in Turkey have only recently been proposed [6] and they are not instated formally to this date.

Requirements and guidelines for parking space design vary depending on the site and the users. Demands and needs of the users of a site, pedestrians and the drivers alike, are the main considerations in designing parking facilities. Authors in [9] recommend regulating quality of parking along with the quantity of parking spaces instead of just the latter, and provide examples from cities to demonstrate improved urban design under double regulation. A level of service (LOS) approach is used to customize the parking spaces that best fits the needs of users [1]. Whereas a qualitative level of service approach chooses between minimum and generous design dimensions, a quantitative level of service approach includes detailed design guidelines that chooses between four design dimensions corresponding to levels of service ranging from highest (LOS A), to tighter dimensions (LOS B, C, and D). It is also possible to mix designs from multiple service levels. Freedom to maneuver (turning radii, ramp slopes, travel distance, number of turns, geometry, etc.), flow capacity (ratio of flow rate to the maximum flow capacity), average wait (number of entry/exit points) are some of the design considerations for each level of service.

Two major factors in selecting between these service levels are the turnover rate and the familiarity of the user to the parking facilities [1]. The turnover rate is defined as the average number of vehicles using a parking space during a day. A lower level of service is acceptable for people using parking facilities if most are regular users and when the level of activity for arriving and departing vehicles is not continuously at high levels throughout the day but there may be short spans of rush periods, say in the morning and in the evening. A university campus, which is also the site we consider in this paper, fits to this situation. As a result, we opt to use tighter design dimensions so that number of stalls that can be fit into a parking lot is maximized for the users (mostly students and staff) who are well familiar to the parking facilities.

Level of service is also related to the efficiency consideration, which is defined as the floor area constructed per space by a design. When considering the space, gross parking area should be taken into account, i.e., the floor area dedicated to parking. Efficiency affects the cost of construction directly, especially in situations where two different designs with the same number of stalls but different efficiencies due to area usage will yield less cost for the one requiring less floor area. In this respect, selection of parking angle depends on the efficiency. On the other hand, number of stalls that can fit into a given area may also depend on the parking angle. All these suggest that rather than manually trying to figure out the best design for a given area, an analytical solution could provide a quicker way of improving the parking layout design.

Except for sophisticated designs for parking facilities (such as Volkswagen's Autotürme, i.e., car towers), designing other more general-purpose parking facilities is commonly considered as part of architects' and civil engineers' tasks. Therefore, not many in other fields have dwelled on other approaches possible for the problem. In our opinion, joint work with those in other fields such as optimization and mathematics could provide more efficient and economical solutions. Among the few who considered an optimization approach for the parking space design, authors in [2] consider an integer programming formulation to maximize the number of stalls in a parking lot of rectangular region. The lot is divided into three regions with outer and inner areas that will house parking bays of only one type of angle within each lot. Although this approach may be acceptable for smaller parking lots, combining various angles in parts of the parking area may result in more efficient solutions for larger spaces. In addition, the authors assume that the lots are designed from scratch and that entry and exit points are located across each other at the midpoints of the longer side of the parking area, which may not be the case for all parking lots. In a peculiar study [4], the authors derive a formula to maximize the number of stalls in a triangular parking area that can be solved using linear integer programming. However, the triangular shape is very uncommon in practice and their model can only accommodate parking angles of less than 90°, which are both very restrictive in general.

We provide an optimization model for the parking layout problem which allows using various parking angles and stall dimensions; and takes into account required access widths without any strong assumptions. The rest of the paper is organized as follows. In § 2, we provide the additional necessary background and terminology. Mathematical model is provided in § 3 followed by the numerical study and its discussions in § 4. Conclusions and possible extensions are given in § 5.

2. Background

A parking lot may contain one or more parking modules. A parking module is the combination of a set of parking bays including parking stalls and aisles between the parking bays. Figure 2 graphically defines 90°, angled, and parallel parking layouts, drive aisles, stall, modules in "single-loaded bay" (a single row of parking spaces on only one side of the drive aisle) as well as in "double-loaded" parking bays with dimensional elements (see also [8], [5], [1]).

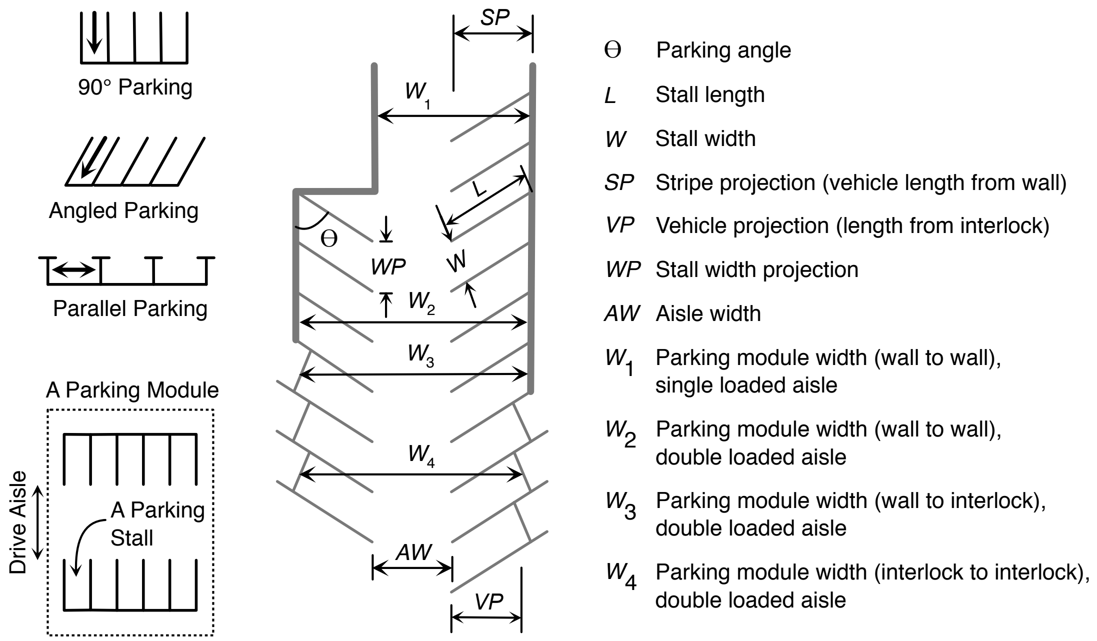


FIGURE 2. Stall and module dimension legend.

Dimensions fundamental to the design of parking lots are stall width and length, drive (or access) aisle width and parking angle, all of which are related to the size of the vehicle. Sizes of vehicles change over time. Figure 3 shows the quantity and percent of registered vehicles by segment in European countries adapted from [7] showing that the set of medium segments has still the largest portion of sales in the market. The same document provides average passenger car dimensions for Turkey in Figure 4, from which it can be deduced that some increase is observed in the average length and width of the passenger car. However, these measures are still within the definition of a standard vehicle size given in literature as displayed in Figure 5 taken from [3].

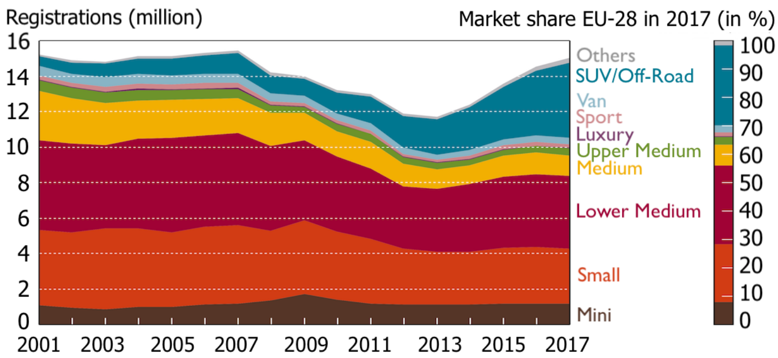


FIGURE 3. New registrations of passenger cars by segment over the years in European market including Turkey in the last four years.

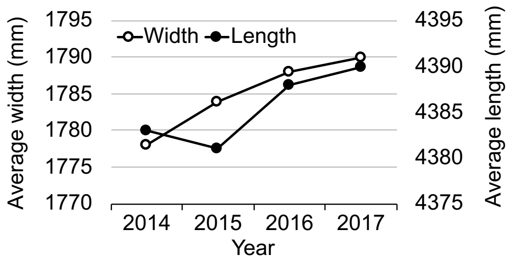


FIGURE 4. Average passenger car dimensions in Turkey through the years.

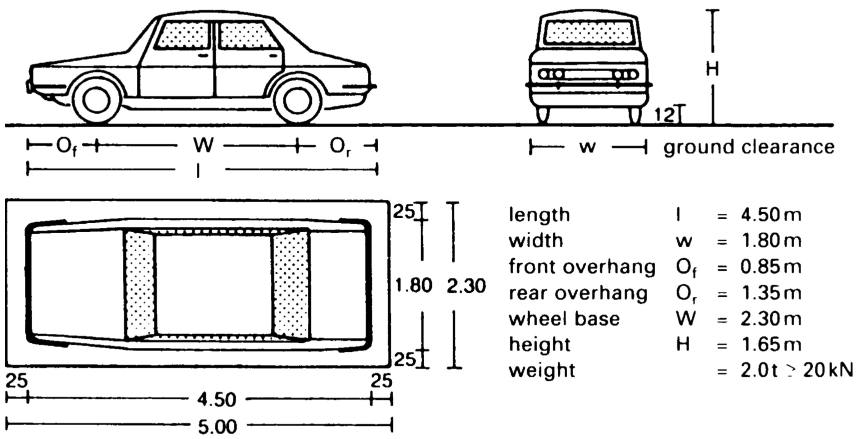
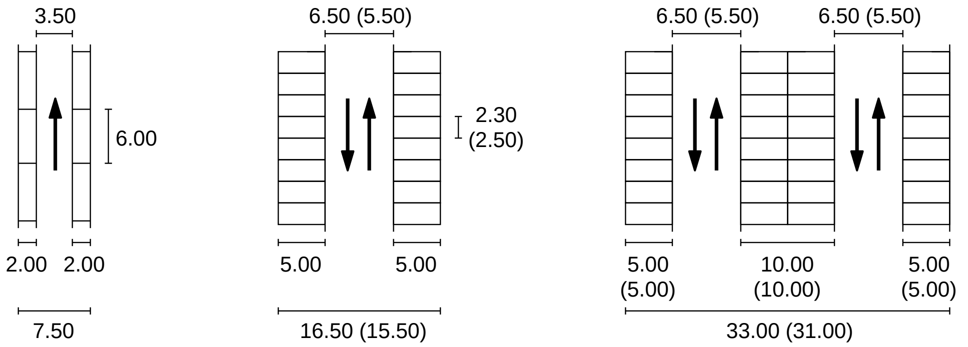
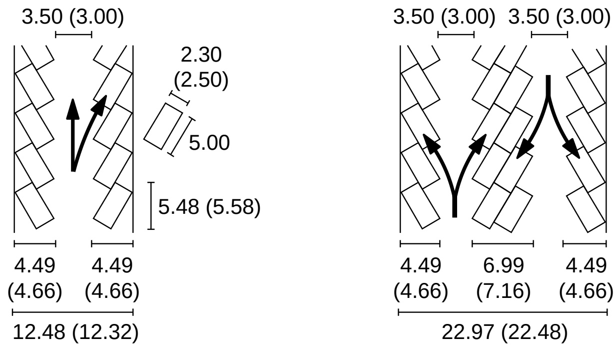


FIGURE 5. Standard passenger car dimensions.

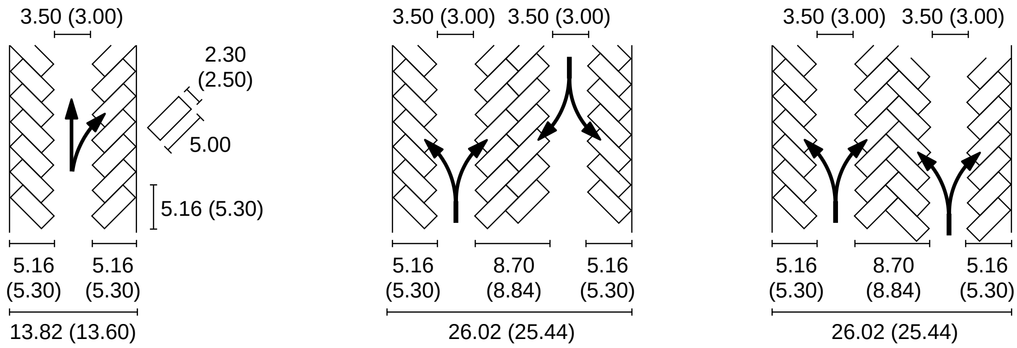
We note that there is not a single agreed-upon standard set of dimensions for designing stalls and parking areas but recommendations to account for maneuvering in and around the parking space safely and without too much discomfort by considering the physical conditions of the parking module such as walls, curbs with or without overhang, parking angle, etc. We refer the reader to [1], [5], and [8] for recommended dimensions at various parking angles and levels of service. Figure 6 shows common parking layout configurations and dimensions considering parking angles of 0° (parallel parking), 30°, 45°, 60° and 90°.



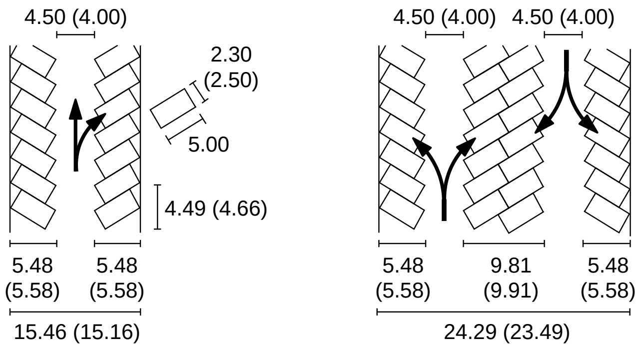
(A) Parallel parking. (B) 90° parking (double loaded). (C) 90° parking with interlocking.



(D) 30° parking (double loaded). (E) 30° parking with interlocking.



(F) 45° parking (double loaded). (G) 45° parking with interlocking. (H) 45° parking with herringbone.



(I) 60° parking (double loaded). (J) 45° parking with interlocking.

FIGURE 6. Common parking layout configurations and dimensions (in meters) based on parking angle for stall width of 2.30m (2.50m).

Efficiency, appropriateness, advantages and disadvantages for angled parking and parking without angle (i.e., parallel and 90° parking) can be summarized as follows:

- 0° ***parallel to road*** works well in narrow and linear spaces. Entry and exit to the stall is difficult.
- 30° ***oblique to road*** works well in busy areas since entry and exit to the stall is simple. It requires relatively smaller width in layout but is for one-way-only aisles.
- 45° ***oblique to road*** is referred to as "normal layout" with simple entry and exit to the stall. It is for one-way-only aisles.
- 60° ***oblique to road*** works well for short-term use in busy areas with simple exit and entry to the stall. However it requires larger width compared with smaller angles and is for one-way-only aisles.
- 90° ***perpendicular to road*** works well for areas with low turnover rate or long term use, and with either one- or two-way aisles. However, entry and exit into the stall requires considerable maneuvering. It is the most efficient in terms of space required per place if the area is sufficient for the required turning bay width.

Angled parking usually requires and wastes more space compared to 90° parking, which offsets its ease in maneuvering (see Figure 7). However, if the area is too narrow to accommodate the latter, then angled parking can be more efficient with less required width for the turning bay and the stall.

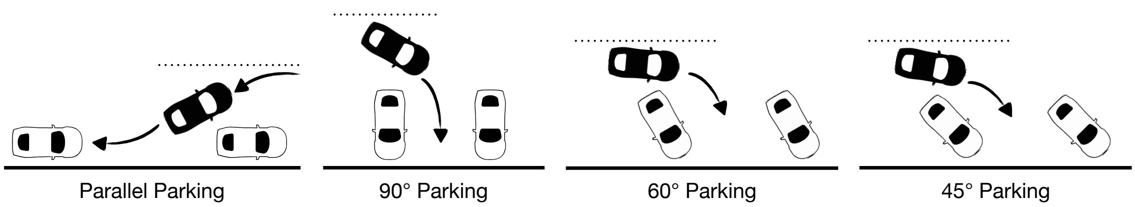


FIGURE 7. Maneuvering at different parking angles.

Required access width for maneuvering, i.e., the minimum aisle width, varies by stall width. Table 1 lists the required access aisle dimensions for two different stall widths at the considered angles.

TABLE 1. Required access width (in meters) at different angles and stall widths (0° parking needs 2m of stall width with access width of 3.5m.)

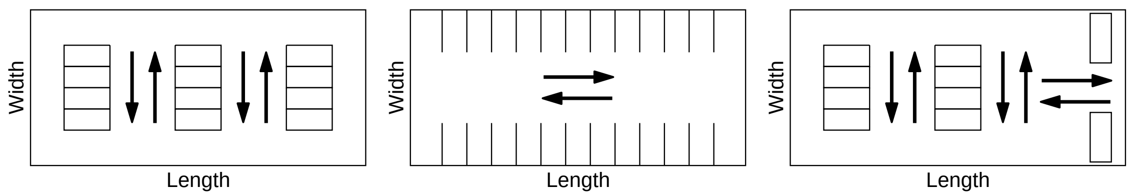
	Access width (m) at parking angle				
Stall width (m)	0°	30°	45°	60°	90°
2.30	3.50	3.50	3.50	4.50	6.50
2.50	3.50	3.00	3.00	4.00	6.00

3. Mathematical Model

We use a knapsack formulation of the bin-packing problem to find the best arrangement of parking stalls inside a rectangular parking lot given a set of possible patterns. The bin-packing problem is a special case of the cutting stock problem, the latter involving finding how to best cut pieces of various dimensions and required quantities from a given standard-sized material in order to minimize the waste. A variation of the cutting stock problem maximizes the value of the produced quantity instead of minimizing waste when orders for pieces have different values. In the bin-packing problem, objects of different volumes are to be packed in standard-size bins in such a way that the number of bins used should be minimum. If the number of bins is one and if objects are differentiated by value and volume, then the objective becomes maximizing the value of items that can be fit in the bin. This is the classical knapsack problem in the Operations Research literature.

In our case, each parking lot can be considered as a bin and since each lot is independent, a separate formulation will be used for each. Therefore, given a set of possible parking patterns, the design problem is to find the optimal arrangement of a set of these patterns that yields the maximum number of parking stalls honoring access widths while fitting in the lot. The optimization problem is NP-hard, and in general, the real difficulty is about generating patterns which can be quite large.

We will refer to arrangement of parking bays in a rectangular parking lot as: *vertical* if the bays are parallel, *horizontal* if the bays are perpendicular, and *mixed* if some of the bays are parallel and the rest are perpendicular to the longest edge of the lot. Figure 8, which illustrates these possible arrangements, indicates that the mixed arrangement results in too much wasted space and may obstruct maneuvering. Therefore, our model includes only horizontal or only vertical arrangement. In other words, the model is solved separately for each type of arrangement, and the one that gives the maximum number of stalls is selected as the best solution to the design problem.



(A) Vertical arrangement. (B) Horizontal arrangement. (C) Mixed arrangement.

FIGURE 8. Possible arrangements of parking bays.

Generation of parking patterns considers the standard car size and the corresponding minimum and medium stall dimensions (5 meters × 2 meters for parallel parking and 5 meters × 2.3 meters for other forms of parking) as well as access aisle widths. We also take into account a slightly more comfortable stall dimension of 5 meters × 2.5 meters. Using common parking layout configurations and dimensions (see Figure 6), we generated a total of 96 patterns with varying parking angles and widths for the stalls and access aisles within. Generation of a pattern is simplified using spreadsheets and through duplicating a pattern to generate multiple interlocks at each of the possible two different stall sizes, and then, preprocessing is done to eliminate those patterns whose widths exceed both the width and length of the rectangular parking lot. Some of the generated patterns are shown in Figure 9.

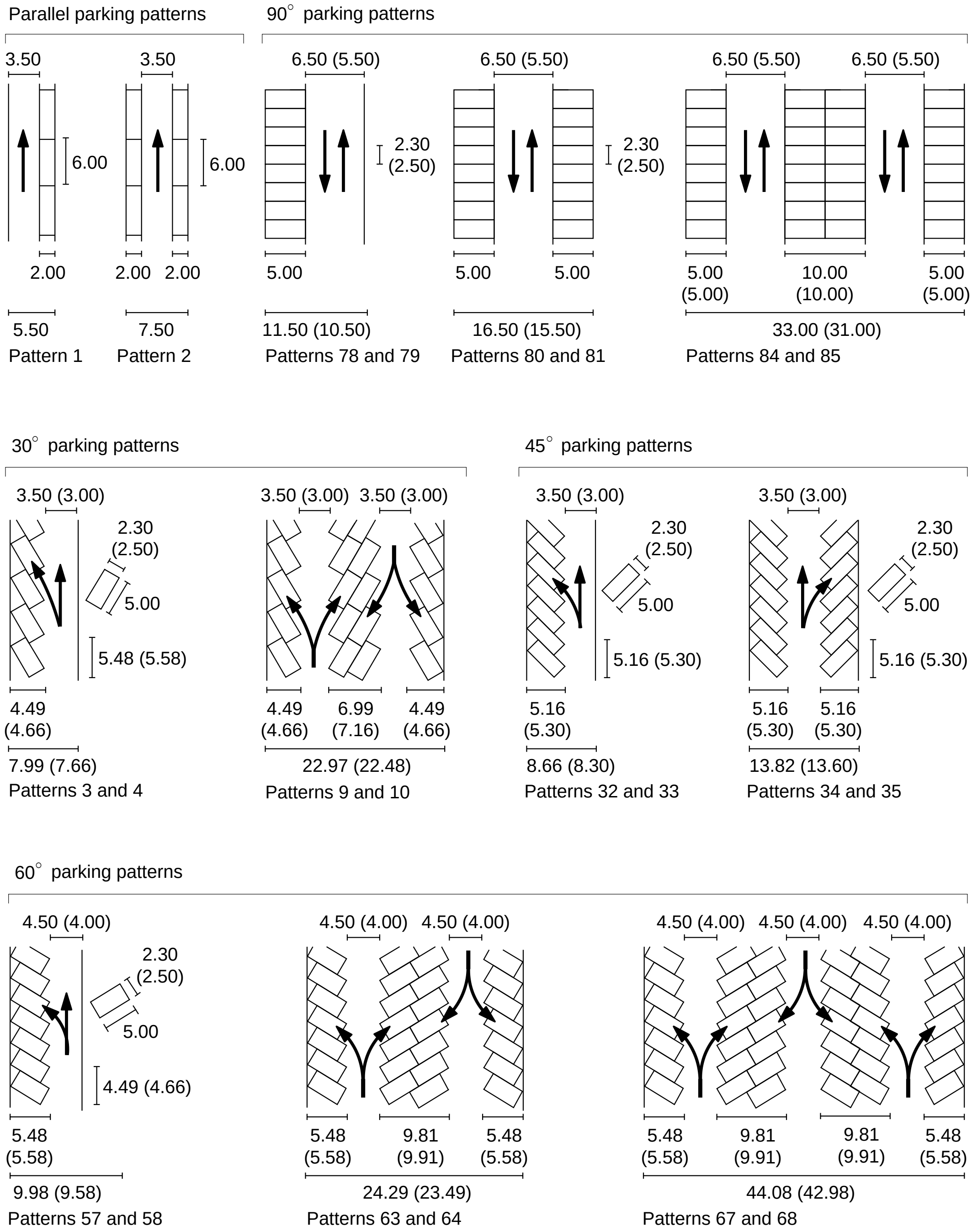


FIGURE 9. Examples of generated parking patterns.

Decision variables, x_i, correspond to the quantity of pattern i placed in a given parking lot and for a given arrangement type (horizontal or vertical) where $i = 1, 2, \ldots, n$ and n is the total number of considered patterns ($n = 96$ in this paper). We label each pattern as P_i, i.e., we have $P_1, P_2, \ldots, P_n$. The integer programming formulation is presented below,

$$\text{Maximize} \quad \sum_{i=1}^{n} s_i \cdot b_i \cdot x_i \tag{1}$$

subject to

$$\sum_{i=1}^{n} w_i \cdot x_i \leq D_\bullet \tag{2}$$

$$x_i \in \mathscr{Z}^+ \qquad i = 1, 2, \ldots, n \tag{3}$$

where

s_i: Number of stalls that can fit in a single bay of pattern i,
b_i: Number of parking bays in pattern i,
w_i: Width of pattern i in meters,
$D_\bullet = D_W$ (D_L) in horizontal (vertical) arrangement,
D_W: Width of the rectangular parking lot under horizontal arrangement in meters,
D_L: Length of the rectangular parking lot under vertical arrangement in meters,
WP_i: Width projection of a stall in pattern i in meters.

Objective function in (1) calculates the total number of stalls in the selected patterns of a given lot whereas the single constraint in (2) ensures that the width (length) in horizontal (vertical) arrangement is not exceeded by the sum of the respective dimension of the selected patterns. Constraint set in (3) imposes non negativity and integrality restrictions on the decision variables.

We note that other sets of constraints can be added to the model in order to prevent mixing of angled-parking layouts in the same lot. For this purpose, define N_j as the set of patterns using the jth parking angle where $j = 1, 2, 3$ correspond to 30°, 45° and 60° degrees, respectively, and additional binary decision variables, a_j, indicating whether the jth parking angle is used in a parking lot. In case angle mixing is undesired, then, naturally, the created patterns should not include any mixing of the angles. If required, all of the different angles can be added to the set to ensure only one parking angle is selected for the whole lot. For the former case, the following constraints can be added to the model on demand.

$$\sum_{i \in N_j} w_i \cdot x_i \leq D_\bullet \cdot a_j \qquad j = 1, 2, 3 \tag{4}$$

$$\sum_{j=1}^{3} a_j \leq 1 \tag{5}$$

$$a_j \in \{0, 1\} \qquad j = 1, 2, 3 \tag{6}$$

Constraint set in (4) ensures that no pattern containing a particular angle can be selected unless that angle is used in the parking lot. Constraint in (5) limits the number of parking angles to at most one of the restricted set of angles. Finally, the last set of constraints in (6) restricts the type of additional variables to binary values.

We note that number of stalls that can fit in a single bay of pattern i, s_i, is calculated by leaving an access aisle on two sides of the parking lot for maneuvering (access width of 5 meters on each side is considered acceptable for turning) based on the type of arrangement and is rounded down to the nearest integer as given in Equation 7.

$$s_i = \begin{cases} \left\lfloor \dfrac{D_L - 10}{WP_i} \right\rfloor & \text{if arrangement is horizontal} \\ \left\lfloor \dfrac{D_W - 10}{WP_i} \right\rfloor & \text{if arrangement is vertical} \end{cases} \tag{7}$$

Values of the parameters b_i, w_i, and d_i for some of the patterns displayed in Figure 9 are given in Table 2.

TABLE 2. Example parameter values for some of the patterns in Figure 9.

Parking angle (degrees)	Pattern (i)	Bays in pattern (b_i)	Stall width projection WP_i	Pattern width w_i
0°	1	1	6.00	5.50
	2	2	6.00	7.50
90°	84	4	2.30	33.00
	85	4	2.50	31.00
30°	3	1	4.60	7.99
	4	1	5.00	7.66
45°	34	2	3.25	13.82
	35	2	3.53	13.60
60°	67	6	2.66	44.08
	68	6	2.88	42.98

The model is solved twice, i.e., considering horizontal and vertical arrangements for each parking lot. We present and discuss the solutions of the model next.

4. Model Solution and Discussion

We used real data to demonstrate the application of our model to a university campus in Ankara, Turkey. Some of the data are obtained from the support services of the university and the rest through observation and measurements. The campus under consideration includes several buildings, sports facilities, a dormitory, green spaces, etc. Currently, it has 410 parking stalls, 300 of which are in the lots we attempt to redesign.

Initially four lots (A, B, C, D) are considered for redesign not only because these are almost always crowded and where irregular parking and parking violations often occur with some vehicles parked haphazardly around blocking other cars and access aisles but also we have an opportunity to see how the model behaves when dimensions of a lot change. Sketches of these parking lots are given in Figure 10 briefly depicting the location of stalls, their angles with respect to the perimeters of the lots and lot dimensions. Note that we divided Lot A into two (A1 and A2) and changed the perimeter of existing Lot A (which is divided by curbs and bushes but still referred to as a single lot), hence we will redesign five lots in total.

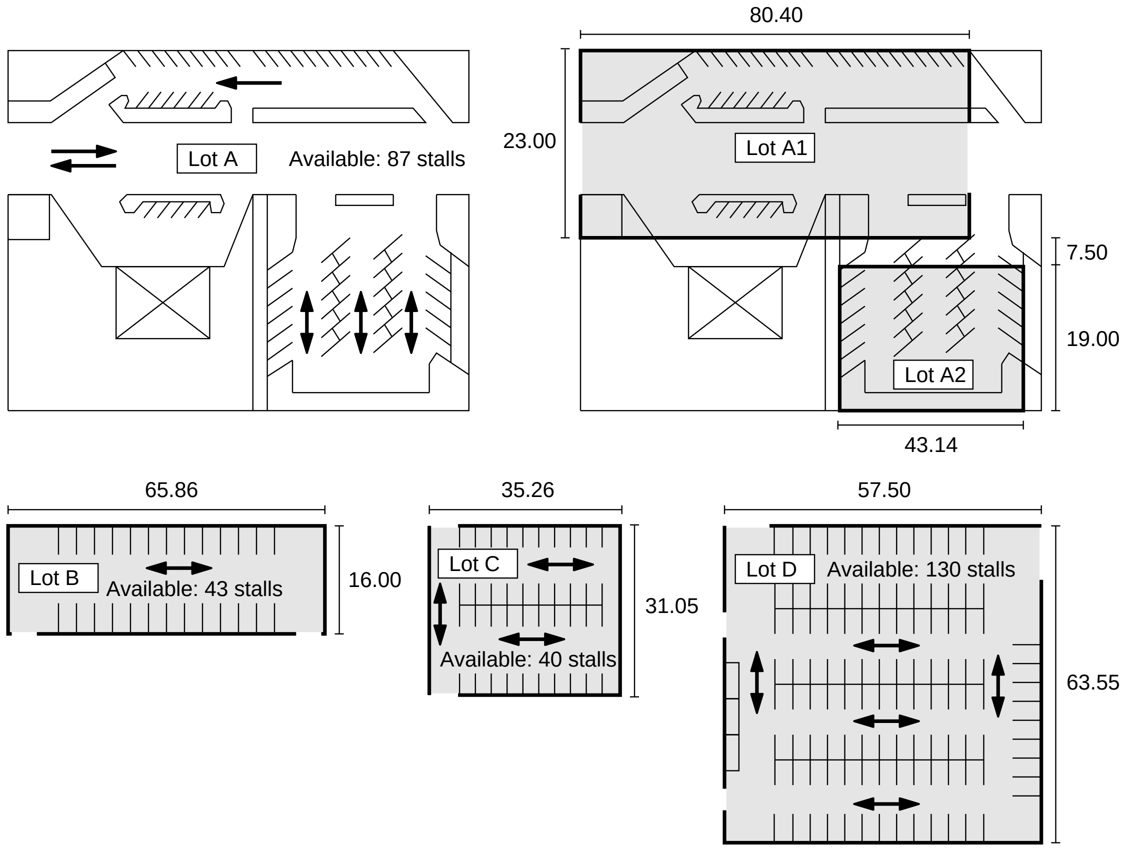


FIGURE 10. Sketches of existing parking lots and new perimeters for the redesign (shaded new lot designs are overlaid on the existing layouts, not to scale and the stall depictions do not represent their counts).

Lots A1 and A2 have curbs and bushes which will need to be removed in the new arrangement. Examining Figure 10, one can notice that lower portion of Lot A, which we will redesign as a separate lot and refer to as Lot A2, has a faulty arrangement. First, the two interlocking patterns in the middle are facing the same direction with each other and the single-loaded bays around them with narrow aisles in between. This kind of placement may require back-parking depending on the direction from which a vehicle is coming. Second, the interlocking mechanism is intended for a one-way-only aisle which is not applied or enforced in this parking lot.

The ordinances proposed in [6] includes requirements relevant to universities. Considerations relevant to the solution of the mathematical model are given below.

- Based on the outlines [6], a university campus should have one parking stall per every 200m^2. The university is built on 74,000 square meters, with almost half the area covered with buildings many of which have three or more stories, requiring more than 550 stalls (estimated) which is more than the existing 410.
- There should be at least one accessible parking area per 20 stalls (not less than one in any case) closest to the entry-exit points and elevators with markings. Markings for accessible parking areas should be renewed as they have become illegible. We assume that accessible stalls can be created by combining adjacent stalls as necessary.
- There should be a designated parking space for bicycles and motorcycles that is at least 1% of the total parking area. Lots specifically designed and marked for bicycles and motorcycles do not currently exist in the campus. We also ignore spacing for bicycles and motorcycles in our model since some of the parking stalls can be converted upon finding a solution.

We solved the model on spreadsheet using Microsoft Excel (2016) Solver add-in since the spreadsheet simplifies generation of patterns and the model has only one constraint other than the integrality and non-negativity requirements on the decision variables. The solution time is under a few seconds, and hence negligible. Given the set of patterns generated, the optimal solutions obtained under each type of arrangement are summarized in Table 3 followed by a description of the notation used in the table.

TABLE 3. Optimal number of stalls and patterns given the set of parking patterns (horizontal arrangements are selected except for Lot D).

	Number of stalls		Patterns selected (Quantity, $\sum_i x_i^* \cdot P_i$, and configuration)	
Parking lot	Horizontal	Vertical	Horizontal	Vertical
Lot A1	78	52	$1P_2$: (0°) $1\cdot1 \mid 1\cdot1$ $1P_{81}$: (90°) $1\cdot1 \mid 1\cdot1$	$1P_{56}$: (45°) $1\cdot1 \mid 1\cdot1$
Lot A2	28	18	$1P_{80}$: (90°) $1\cdot1 \mid 1\cdot1$	$1P_{68}$: (60°) $1\cdot1 \mid 2\cdot2 \mid 1\cdot1$
Lot B	44	18	$1P_{81}$: (90°) $1\cdot1 \mid 1\cdot1$	$1P_2$: (0°) $1\cdot1 \mid 1\cdot1$ $1P_{60}$: (60°) $1\cdot1 \mid 1\cdot1$ $1P_{68}$: (60°) $1\cdot1 \mid 2\cdot2 \mid 1\cdot1$
Lot C	40	36	$1P_{85}$: (90°) $1\cdot1 \mid 1\cdot2 \mid 1\cdot1$	$1P_{84}$: (90°) $1\cdot1 \mid 1\cdot2 \mid 1\cdot1$
Lot D	154	154	$1P_2$: (0°) $1\cdot1 \mid 1\cdot1$ $3P_{80}$: (90°) $1\cdot1 \mid 1\cdot1$	$1P_{80}$: (90°) $1\cdot1 \mid 1\cdot1$ $1P_{81}$: (90°) $1\cdot1 \mid 1\cdot1$ $1P_{85}$: (90°) $1\cdot1 \mid 1\cdot2 \mid 1\cdot1$

We show patterns by parking degree followed by the usage count of a bay times the bay configuration showing single (denoted as 1) and interlocking mechanisms (denoted as 2) from left to right of a pattern with vertical bars for aisles. Multiple quantities of a bay configuration is assumed to include access aisles between them and will not be shown with a vertical bar. As an example $(60^\circ)\ 1 \cdot 1 \mid 2 \cdot 2 \mid 1 \cdot 1$ corresponds to pattern 68 in Figure 9, indicating that the pattern starts with one single bay, followed by two interlocking mechanisms and ends with one single bay.

It can be observed from the solutions obtained that vertical arrangement favors angled parking for some lots (Lots A1, A2, part of lot B), whereas horizontal arrangement opts for mostly 90° and and some parallel parking layout in the remaining area. Although 90° parking is the most efficient in terms of the area required per space, together with the arrangement type, width and length of the parking lot will have to be used in the most efficient way to maximize the number of stalls fit in the lot. Under vertical arrangement, a combination of relatively small width and large length of the parking lot leads to more efficient usage of the length of the parking lot through smaller pattern widths associated with angled parking. Sketches of the redesigned parking lot layouts based on the selected arrangement types, numbers and dimensions of stalls in each lot are provided in Figure 11.

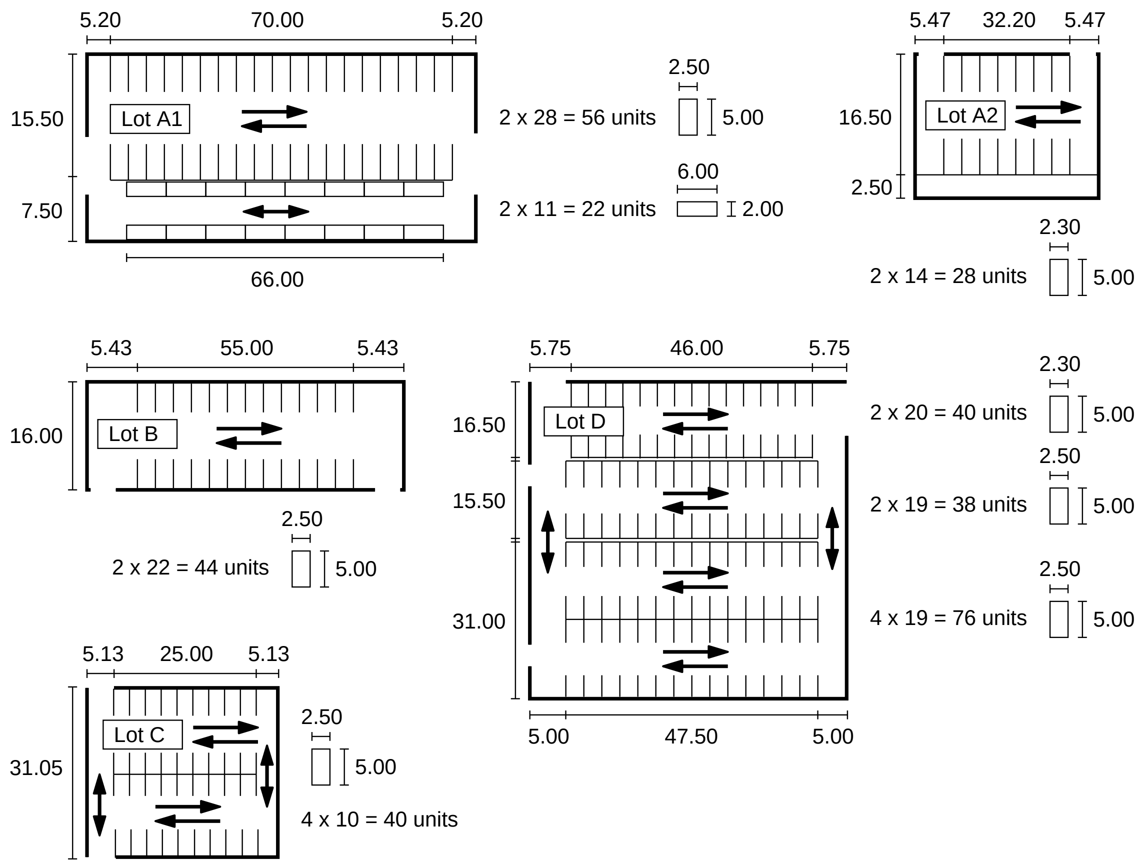


FIGURE 11. Sketches of redesigned lots with dimensions and quantities of stalls (not to scale and the stall depictions do not represent their counts).

The number of stalls is higher under horizontal arrangement except for Lot D which has equal number of stalls under both horizontal and vertical arrangements. This particular parking lot has relatively larger width and length combination compared with other lots, which may lead to symmetry in arrangement. We select the horizontal arrangement for all lots but Lot D, considering the exit and entry points located in the parking lots. For Lot D, the vertical arrangement which has the same number of stalls under horizontal arrangement provides a layout that aligns better with the existing entry and exit points.

A comparison of the existing and redesigned parking lots with respect to number of stalls is given in Table 4. Except for Lot C, additional stalls can be gained by redesigning the parking lots, bringing a total of 44 extra stalls, an approximately 15% increase from the current situation. The additional stalls, although not sufficient to bring the total number to the required ordinance number, would certainly lessen the burden of looking for a parking spot.

TABLE 4. Comparison of existing and redesigned parking lots.

	Number of stalls		Additional stalls	Percent improvement
Lots	Current	Proposed	gained	from current configuration
A1+A2	87	106	19	21.84
B	43	44	1	2.33
C	40	40	-	-
D	130	154	24	18.46
Total	300	344	44	14.67

Finally, redesign of lots will require markings, parking guides and signs in all lots (except for Lot C since the proposed solution is the same as the existing one) to be remade, removal of all existing curbs and bushes, and transplantation of some trees in Lots A1 and A2. In addition, paving has to be renewed in these two lots. Therefore, the corresponding costs need to be taken into account.

5. Conclusions

We provided a cutting-stock formulation for (re)designing rectangular parking lots in order to maximize the number of stalls while satisfying access aisle width requirements. Generation of patterns, which is the most complicated part of the formulation, is simplified through using common parking layout configurations and adjoining them through interlocking patterns via spreadsheets. The solutions for the application of the model to a university campus yielded improvements up to 22% per lot without a major overhaul of the existing space. An extension of this study may consider a bi-objective formulation with cost minimization or simply a budget constraint.

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