

Optimizing parking lot design by Generative design approach

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Abstract. The article describes how to transform the time-consuming process of selecting design solutions for parking spaces according to regulatory requirements and terms of reference by building information modelling (BIM). The main purpose of the work is to determine the possibility of applying a generative approach to the parking lot design by creating an optimization model of variant design. The process of selecting design solutions for parking is considered by using mathematical modeling and multi-criteria optimization. A mathematical description of finding the optimal solution on the region of admissible ratios is obtained both between the two types of parking spaces required by regulatory documents (type 1-Standard, with dimensions of 5.3 x 2.5 meters; type 2 - for People with Limited Mobility (PLM), with dimensions of 6.0 x 3.6 meters) and between the occupied area and the total number of parking spaces. The optimization model of choosing design solutions for parking lot helps a design engineer to adapt changes in requirements for defining admissible options for space-planning solutions. The study proves that the task of choosing admissible and optimal solutions for the parking lot, depending on the set of conditions, can be performed by using algorithms, and, consequently, by using computer-aided design in BIM. The proposed approach to parking lot design allows the project organization to coordinate the initial conditions and solutions between the project participants and related departments, and also serves as the basis for solving subsequent design tasks, such as determining the economic efficiency, the safety of the parking project, and others.

1 Introduction

The land allocation for parking spaces has now become a significant part of the territorial and urban planning. The increasing speed of infrastructure development leads to a lack of free areas for storing vehicles, what often observed in large cities, historical buildings areas, or cramped conditions.

The optimal design solution choice of the parking lot must meet the requirements, that sometimes contradict each other: urban planning, transport, operational, economic, and safety requirements [1].

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This paper is prepared on the analysis of sources, describing the approach of choosing design solutions as an optimization process, that allows to codify and expand the possibilities for automation in the project documentation preparation [2,3,4].

The issue of optimizing the vehicles storage is considered in several research with consideration the problem of optimal placement on the ship's decks for the transport of wheelbase cargo, taking into account the requirements for transportation, including fire safety, ship stability, loading, and unloading time [5, 6].

The effective placement choice of parking spaces on the available area, taking into account the regulatory requirements and terms of reference, is a comparison of various options for space-planning solutions [1, 7]. Obtaining quantitative characteristics for comparison by the direct design method some possible options for the placement of parking spaces is a time-consuming process. Therefore, it is necessary to identify a way to improve the choice of parking space placement by using multi-criteria optimization methods, which will serve as the basis for a Generative design approach to the parking lot design.

Generative design (lat. generatum – "generate, produce") is found as one of the strategic directions, that represent the design process as the result of exclusively mathematical calculations generated by the CAD system (computer-aided design) [8, 9], which has been already applied for the optimization of the systems geometry [10, 11] and spatial planning issues [12, 13].

2 Methods

According to the mathematical modeling method, the process of placing parking spaces on the available parking area within the regulatory requirements is considered in the form of sequential subprocesses:

1. selection the optimal composition of parking spaces in the available parking area;
2. determination of possible options for the selected composition of parking spaces placement;
3. evaluation the options for placing the selected composition of parking spaces and determining the optimal option according to the initial criteria.

Subprocess 1 represents a multi-criteria optimization problem with the condition of which is formed as follows:

Any parking should provide two types of parking spaces. Type 1 is spaces with dimensions of 5.3 x 2.5 (Standard), type 2 is parking spaces with minimum permissible safety clearances with dimensions of 6.0 x 3.6 for People with Limited Mobility (for PLM) are provided in the parking lot. It is required to provide at least 50 parking spaces in general. The number of parking spaces for PLM should be at least 10% of the total number, but not less than 1 parking space [14]. The area of open surface car parking should not exceed 2400 m², and 40% of the total area of parking spaces is allocated for a parking passage (the area that is not occupied by cars). It is necessary to determine the number of parking spaces of each type, which corresponds to the maximum number of parking spaces and the minimum parking area.

The purpose of parking lot design is to achieve two objective functions:
function 1 – obtaining the maximum possible number of parking spaces;
function 2 – obtaining the minimum area of the Parking lot.

The initial data is summarized in Table 1:

Table 1. The Initial data for the task of choosing the optimal composition of parking spaces in an available parking area.

| Criteria | UOM | Evaluation | Value |
|--|----------------|------------------|---------|
| Available area of the parking lot | m ² | not greater than | 2400 |
| Required part of the area for passage from the total area of the parking lot | % | equal | 40 |
| Required number of parking spaces | pc. | not less than | 50 |
| Required part of parking spaces for PLM of the total number | % | not less than | 10 |
| Required number of parking spaces for PLM | pc. | not less than | 1 |
| Dimensions of type 1 parking space, standard | m | equal | 5,3×2,5 |
| Dimensions of type 2 parking space, for PLM | m | equal | 6,0×3,6 |

To make a mathematical description for the task, following variables and numerical features have been declared.

x_1 – number of type 1 parking space, standard, pc.;

x_2 – number of type 2 parking space, for PLM, pc.;

– area of type 1 parking space, m²:

$$5,3 \cdot 2,5 = 13,25 \quad (1)$$

– area of type 2 parking space, m²:

$$6,0 \cdot 3,6 = 21,6 \quad (2)$$

– area of parking spaces, m²:

$$13,25 \cdot x_1 + 21,6 \cdot x_2 \quad (3)$$

– area of parking passage, m²:

$$0,4 \cdot (13,25 \cdot x_1 + 21,6 \cdot x_2) \quad (4)$$

– total area of the parking lot, m²:

$$1,4 \cdot (13,25 \cdot x_1 + 21,6 \cdot x_2) \quad (5)$$

– total number of parking spaces, pc.:

$$x_1 + x_2 \quad (6)$$

– ratio between the parking spaces types (7) convert to the inequality (8):

$$x_2 \geq (x_1 + x_2) \cdot 0,1 \quad (7)$$

$$x_1 - 9 \cdot x_2 \leq 0 \quad (8)$$

The optimization model for the initial formulation of the problem keeps the tendency of the maximum number of parking spaces and the minimum parking lot area:

$$x_1 + x_2 \rightarrow \max \quad (9)$$

$$1,4 \cdot (13,25 \cdot x_1 + 21,6 \cdot x_2) \rightarrow \min \quad (10)$$

The restrictions are formed based on the initial data.

– number of parking spaces not less than 50 pc.:

$$x_1 + x_2 \geq 50 \quad (11)$$

– number of parking spaces for PLM not less than 10% of the total number:

$$x_1 - 9 \cdot x_2 \leq 0 \quad (8)$$

– number of parking spaces for PLM not less than 1 pc.:

$$x_2 \geq 1 \quad (12)$$

– area of parking lot not more than 2400 m²:

$$1,4 \cdot (13,25 \cdot x_1 + 21,6 \cdot x_2) \leq 2400 \quad (13)$$

– number of parking spaces nonnegative and integer:

$$x_1, x_2 \geq 0; x_1, x_2 \in \mathbf{Z} \quad (14)$$

The task belongs to the field of linear programming because all relations are fully described by linear functions [15].

The solution to the problem is based on the Preemptive Goal Programming method applied to linear models with the addition the assessment criteria (goals) according to the importance hierarchy. The solution is found by sequentially solving a number of problems with a single-objective function in such a way that solving a problem with a less important goal cannot worsen the optimal value of the objective function with a higher priority. A satisfactory solution to the task under consideration is obtained as a result [16].

To formalize the goals, the expected quantitative values of the objective functions and deviation variables have been introduced in the restrictions, which characterize the degree of achievement the set goals.

For the goal 1, it is assumed that 50 pieces are the standard number of parking spaces for the project. The following deviation variables have been introduced to make the first targeted restriction: d_1^- – is a "deficient" variable that shows the number of parking spaces that is less than 50 pc; d_1^+ – is a "redundant" variable that shows the number of parking spaces that is greater than 50 pc. The variable d_1^+ is responsible for the deviation of the first goal:

$$x_1 + x_2 + d_1^- - d_1^+ = 50 \quad (15)$$

$$d_1^-, d_1^+ \geq 0 \quad (16)$$

For the goal 2, the "deficient" variable d_2^- shows how much the area of the parking lot is less than 2400 m², d_2^+ – is a "redundant" variable that shows how much the area of the parking lot is greater than 2400 m². The variable d_2^- is set to achieve the second goal, if $d_2^- = 0$, then the goal is achieved. The second goal programming takes the form:

$$1,4 \cdot (13,25 \cdot x_1 + 21,6 \cdot x_2) + d_2^- - d_2^+ = 2400 \quad (17)$$

$$d_2^-, d_2^+ \geq 0 \quad (18)$$

The flexibility of "deficient" and "redundant" variables allows linear programming to reach a compromise solution.

In subprocess 2, the options for placing the selected number and composition of parking space types on the parking lot area are determined with the identification the numerical characteristics of each option by the brute-force search.

At the final stage (subprocess 3), a selection the best option to place parking spaces is made by solving the optimization task. The numerical features determined at the previous stages or other indicators, introduced by a decision-maker can be considered as criteria for the analysis of options to place parking spaces.

In this paper, a graphical solution to the multi-criteria problem of choosing the optimal parking spaces composition on the available parking area (subprocess 1) is considered by using the preemptive method.

3 Results

In the initial parking task with two objective functions, the priority is taken for function 1. The selection of the optimal composition for Subprocess 1 includes three stages.

At the first stage, the region of feasible solutions of the problem is determined (Fig. 1), which is described by the system of inequalities:

$$x_1 + x_2 \geq 50 \quad (11)$$

$$x_1 - 9 \cdot x_2 \leq 0 \quad (8)$$

$$x_2 \geq 1 \quad (12)$$

$$1,4 \cdot (13,25 \cdot x_1 + 21,6 \cdot x_2) \leq 2400 \quad (13)$$

$$x_1, x_2 \geq 0; x_1, x_2 \in \mathbf{Z} \quad (14)$$

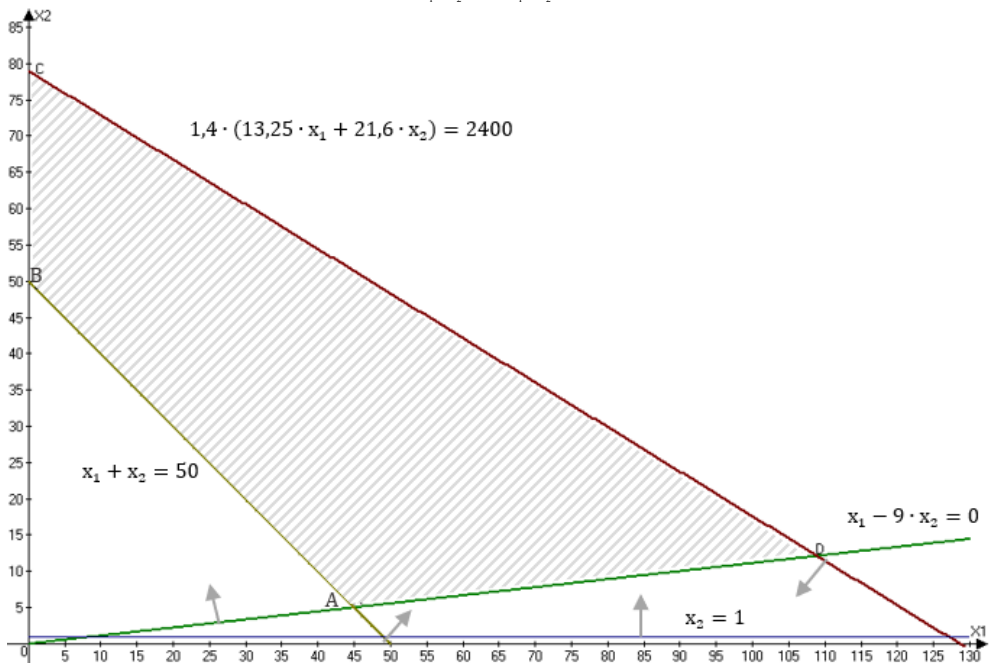


Fig.1. The region of admissible solutions (ABCD)

The second stage includes the task of finding the maximum "redundant" deviation for goal 1 ($d_1^+ \rightarrow \max$) on the region of admissible solutions considering restrictions:

$$x_1 + x_2 \geq 50 \quad (11)$$

$$x_1 - 9 \cdot x_2 \leq 0 \quad (8)$$

$$x_2 \geq 1 \quad (12)$$

$$1,4 \cdot (13,25 \cdot x_1 + 21,6 \cdot x_2) \leq 2400 \quad (13)$$

$$x_1, x_2 \geq 0; x_1, x_2 \in \mathbf{Z} \quad (14)$$

$$x_1 + x_2 + d_1^- - d_1^+ = 50 \quad (15)$$

$$1,4 \cdot (13,25 \cdot x_1 + 21,6 \cdot x_2) + d_2^- - d_2^+ = 2400 \quad (17)$$

$$d_1^-, d_1^+, d_2^-, d_2^+ \geq 0 \quad (16, 18)$$

The maximum "redundant" deviation for goal 1 is achieved at the point with coordinates $x_1 = 108, x_2 = 12, \max d_1^+ = 120 - 50 = 70 pc$.

The third stage includes the task of finding the maximum "deficient" deviation for the goal 2 ($d_2^- \rightarrow \max$) considering restrictions:

$$d_1^+ = 70 \tag{19}$$

$$x_1 + x_2 \geq 50 \tag{11}$$

$$x_1 - 9 \cdot x_2 \leq 0 \tag{8}$$

$$x_2 \geq 1 \tag{12}$$

$$1,4 \cdot (13,25 \cdot x_1 + 21,6 \cdot x_2) \leq 2400 \tag{13}$$

$$x_1, x_2 \geq 0; x_1, x_2 \in \mathbf{Z} \tag{14}$$

$$x_1 + x_2 + d_1^- - d_1^+ = 50 \tag{15}$$

$$1,4 \cdot (13,25 \cdot x_1 + 21,6 \cdot x_2) + d_2^- - d_2^+ = 2400 \tag{17}$$

$$d_1^-, d_1^+, d_2^-, d_2^+ \geq 0 \tag{16, 18}$$

The optimal solution is the point $E (108;12)$ displayed in Fig. 2, $\max d_1^+ = 70 pc$, $\max d_2^- = 2400 - 1,4 \cdot (13,25 \cdot 108 + 21,6 \cdot 12) = 33,7 m^2$.

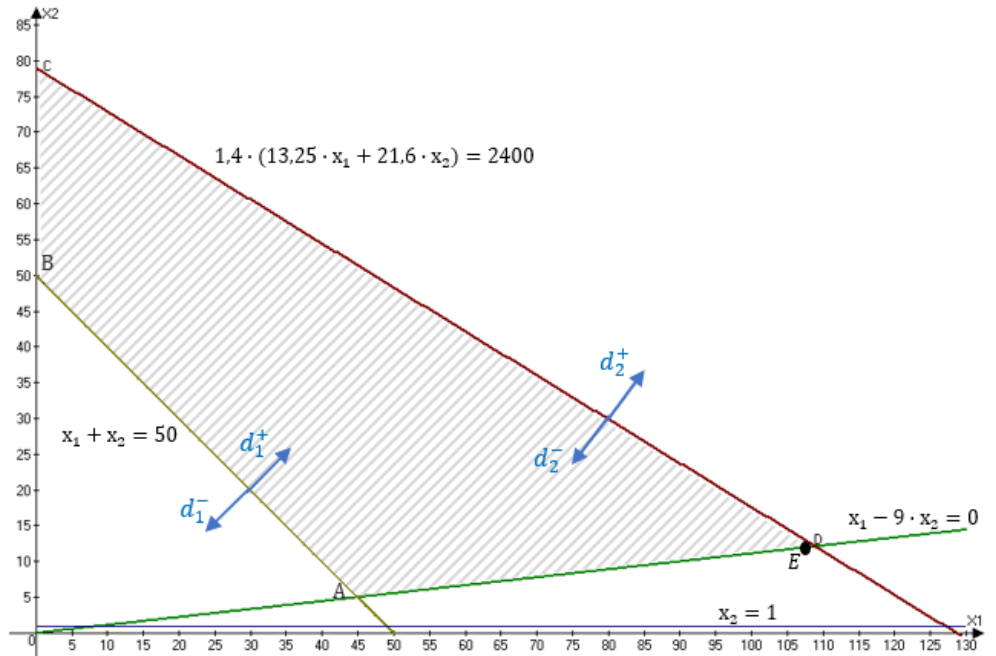


Fig.2. The displaying of the optimal solution (point E) on the region of admissible ratios between two types of parking spaces (type 1, Standard parking spaces - axis X_1 ; type 2, parking spaces for PLM - axis X_2).

To determine the relation between the total number of parking spaces and the occupied parking area, we introduce variables (S, N) and consider the system of equations (21) as follows :

S – area of the parking lot, m^2 ;

total number of parking spaces, pc .:

$$N = x_1 + x_2 \tag{20}$$

$$\begin{cases} x_1 - 9 \cdot x_2 = 0 \\ 1,4 \cdot (13,25 \cdot x_1 + 21,6 \cdot x_2) = S \end{cases} \Leftrightarrow \begin{cases} x_1 = 9 \cdot x_2 \\ 1,4 \cdot (13,25 \cdot x_1 + 21,6 \cdot x_2) = S \end{cases} \Leftrightarrow \begin{cases} x_1 = 9 \cdot x_2 \\ x_2 = \frac{S}{197,2} \end{cases} \quad (21)$$

then:

$$N = x_1 + x_2 = 10 \cdot x_2 = 10 \cdot \frac{S}{197,2} = \frac{S}{19,72} \quad (22)$$

$$S = 19,72 \cdot N \quad (23)$$

The received linear relation between the occupied area and the total number of parking spaces (23), compiled by requirements, is shown in Fig. 3.

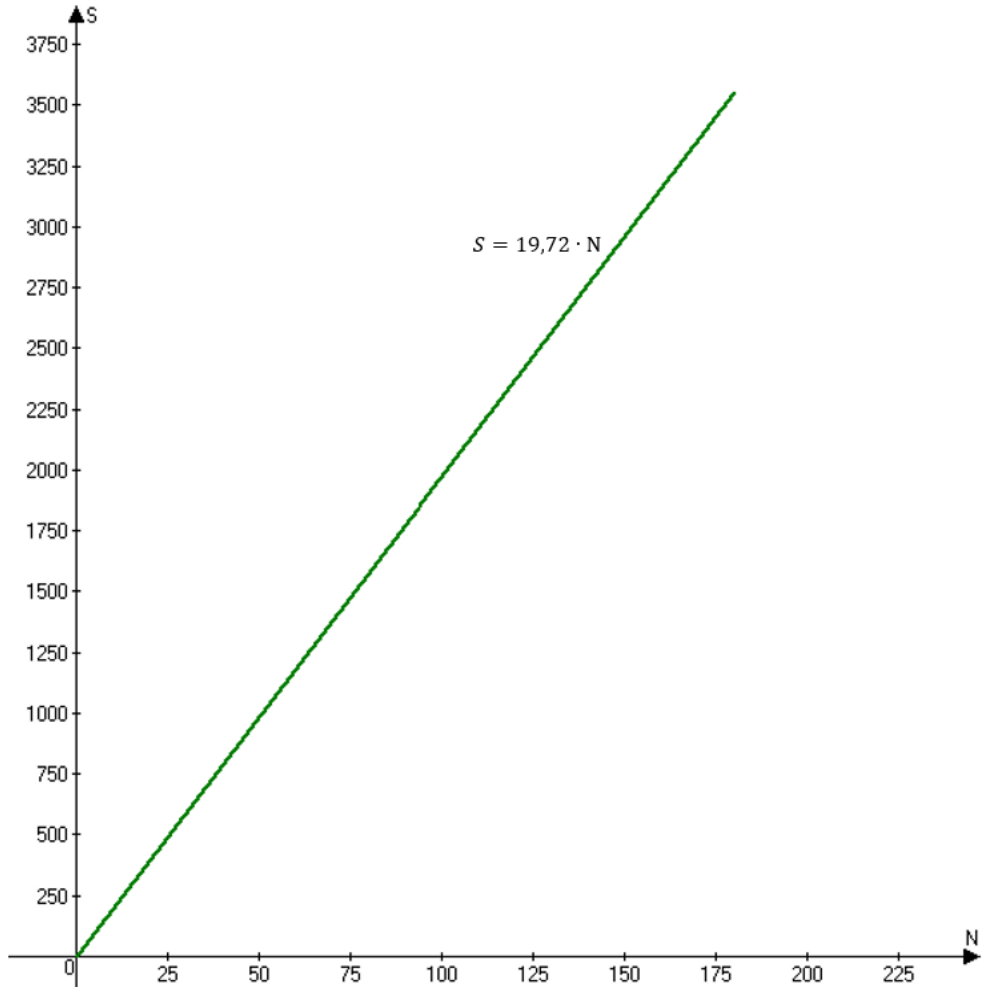


Fig. 3. The relation between the number of parking spaces N and the occupied area S .

The region of admissible solutions to the problem (the shaded area in Fig. 4) and the optimal solution which corresponds to the point F (120; 2366,3) is obtained by adding restrictions on the maximum area and the minimum number of parking spaces:

$$1,4 \cdot (13,25 \cdot x_1 + 21,6 \cdot x_2) \leq 2400 \quad (13)$$

$$x_1 + x_2 \geq 50 \quad (11)$$

$$x_1, x_2 \geq 0; x_1, x_2 \in \mathbf{Z} \tag{14}$$

The optimal solution for the parking lot corresponds to the point whose abscissa is the largest integer on the region of admissible solutions (Fig. 4).

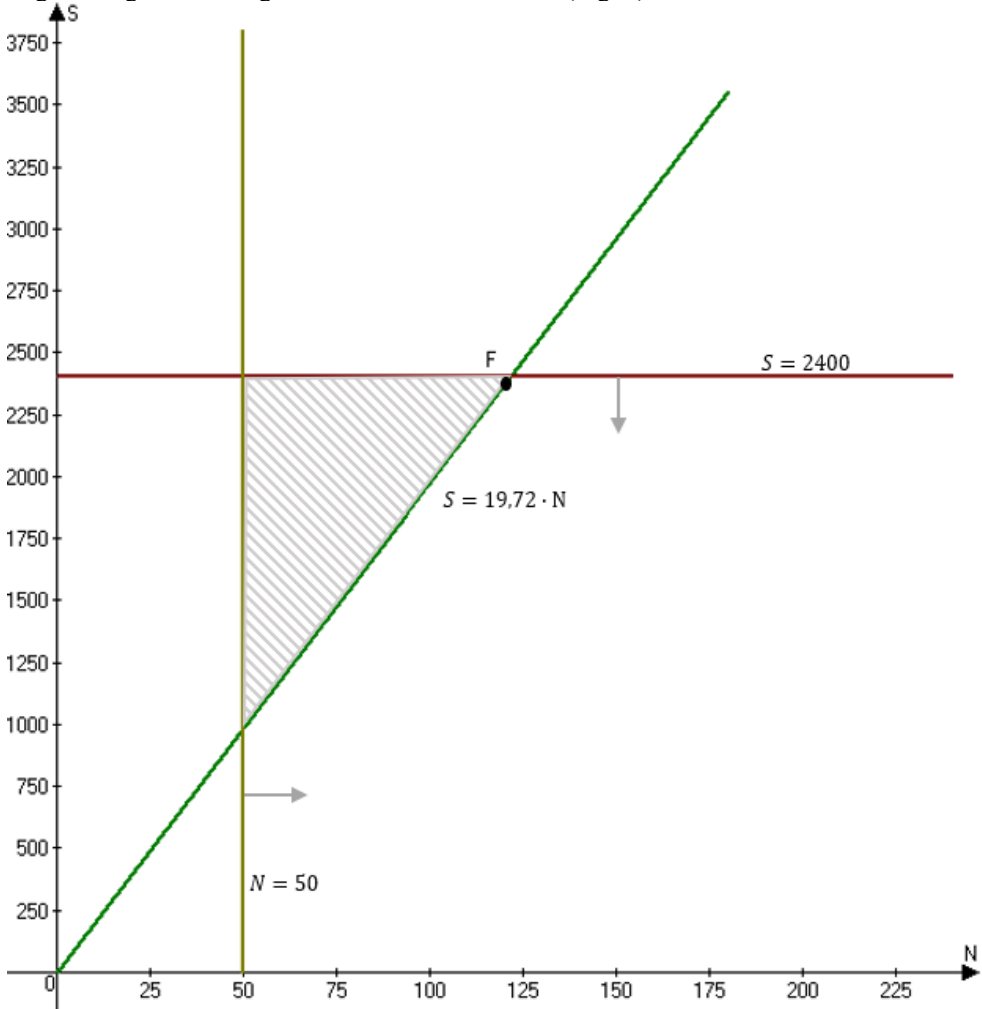


Fig. 4. The displaying of the optimal solution on the region of admissible ratios between the occupied area S and the total number of parking spaces N

4 Discussion

The graphical representation of choosing the optimal parking spaces composition on the available parking area (Fig.2) allows us to draw the following conclusions:

- the optimal number and composition of parking spaces according to requirements is determined at the point E (108 spaces for type 1, 12 spaces for type 2);
- as the available parking area increases (decreases), the optimal number of parking spaces will shift along the OD ray that goes out from the origin, described by the equation;
- with an increase (decrease) in the percentage of parking spaces for PLM from the total number of the angle between the OD ray and the X_1 axis will increase (decrease), and the region of admissible solutions to the problem will decrease (increase).

The revealed graphs (Fig. 2, Fig.4) have practical application for some tasks in the parking lot design:

- establishing the physical possibility for organizing the required number of parking spaces on the available parking area (possible only for points belonging to a region of admissible solutions);
- determination the optimal number and composition of parking spaces on the available parking area according to the requirements for the minimum number of parking spaces for PLM;
- tracking the changes in the set of admissible solutions and the optimal solution because of the modification the technical task (the minimum number of parking spaces) and regulatory requirements (the minimum number of parking spaces for PLM, the ratio between types of parking spaces).

Optimization models, compiled during the selection of the composition of parking spaces on the provided area, serve as the base for solving subsequent design problems. For example, the definition the cost or resources to organize different variants of the parking lot. The coordination of these tasks affects the quality and duration the project stage, as well as the speed of the decision-making process with the probability of changes in the initial data.

The resulting optimization model is not only a design solution, but also a concept. It can be manipulated, which makes design easier and provides the user a mechanism to find acceptable results.

5 Conclusions

The Design of Parking lot according to requirements is represented using the optimization methods, that allow to select a region of admissible solutions, to obtain the ratio between the numbers of different types of parking spaces, to identify the relation between the occupied area and the total number of parking spaces, and to determine the optimal solution.

The created mathematical model for choosing design solutions for parking lots is a proof of the possibility to automatize the design stages in which a person acts as a decision-maker. At the same time, calculating admissible and optimal solutions can be performed by algorithms integrated in software packages for BIM.

The proposed approach for parking lot design allows designers to coordinate and adjust the initial data to decisions made between project participants or related departments, and also adapt the changes of regulatory requirements and technical task at different project stages.

It is worth noting that the area for a passage of the surface car parking was accepted conditionally (40% of the total area). It is assumed, that to detail the initial task, this ratio should reflect the physical possibility of parking organizing. Despite the relation between the number of parking spaces and the available area established in this paper, the relation between the area of parking spaces and the type of parking (ground, underground, mechanized) or garage passage or different angles of placement, or other conditions require a separate study.

The subsequent study of the problem under consideration aims to develop a method for applying Generative design to the entire process of parking lot design by adding restrictions to the mathematical model such as the requirements of economic efficiency, fire safety, and etc.

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