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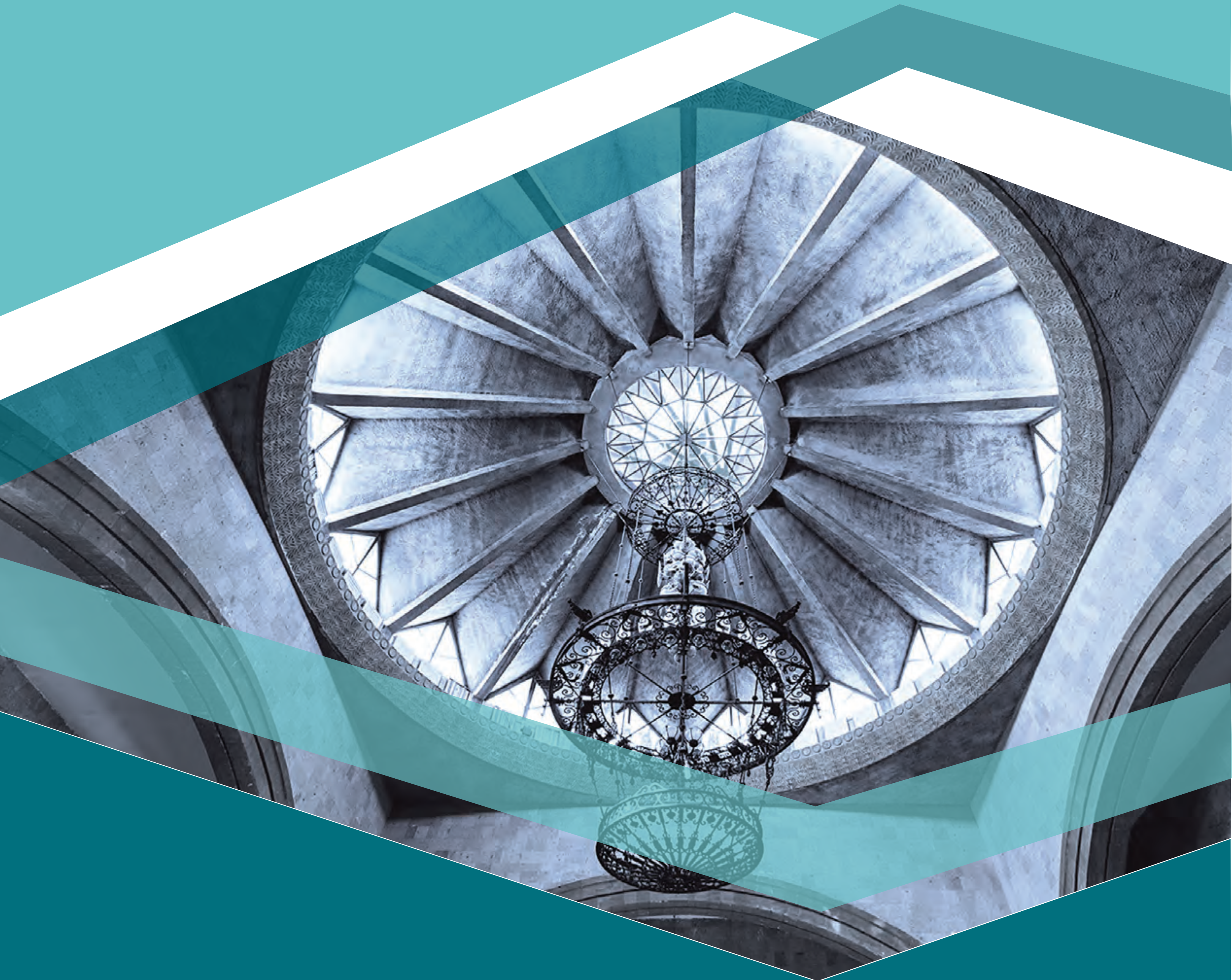

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CONTENT

REGRESSION MODELLING OF SERVICE LIFE PREDICTION OF EXTERNAL WALL PAINTING OF ALGIERS BUILDING

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Abstract: *Paint coatings, as a protective layer of external wall building envelopes, are mainly exposed to several degradation agents, including environmental and climate factors. In the case of North African countries, there are no studies about the estimation of the performance of this coating exposed under the conditions of these regions during its service life. For this purpose, this paper presents a statistical study on the evolution of service life (SL) prediction for external wall painting, based on the inspection of the degradation state of 45 building facades located in Algiers, Algeria. The selection of different investigated external wall paintings is mainly focused on considering their age, the distance from the coastal zone, and the facade orientations. The degradation severity of selected coatings was also estimated in this work using the calculation of a numerical index (Sw). Simple regression analysis (graphical method) and multiple linear regression analysis (MLR) are used for the development of a mathematical model. The main results of this work indicate clearly a high correlation between the values predicted by the mathematical model, which corresponds to a high value of coefficient of determination of 0.95. A comparison study is also conducted in this investigation work between the performance of the obtained model and the MLR model developed by previous research about the SL prediction of paint coating. As a result, the obtained model during this study gives good precision despite the moderate quantity of considered external wall painting.*

Keywords: *External facades painting, Degradation severity, Degradation agents, Service life prediction.*

Introduction

Nowadays, the good quality and the sustainability of building materials are very important for the good stability of social and economic conditions of modern cities. The concept of sustainability translates to the ability of building elements to present during their SL a high performance in a specific environmental condition, without any repair and renovation process on their surfaces. In reality, the durability characteristic is not limited specifically to a fundamental quality of a building material; simple improvement in material properties could impact better protection of its resistance to the different agents of degradation, which leads to an increase in its SL. Although the materials used in the construction field have become more durable, the aging process of these elements is inevitable. This factor can adversely affect the initial characteristics and performances of each construction element [1]. This loss of performance occurring at an early age is certainly not in agreement with the requirements for sustainable construction materials. Thus, various degradations occur during the SL of these construction elements, and their intensities are generally related to the different environmental and climatic factors. In this context, the role of the coating applied to the external facade wall of the building is defined as a protective layer resistant to these various degradation factors.

Among the most common coatings used for the external wall of building envelopes, the paint coating attracts considerable attention due to its different characteristics, which offer several advantages compared to other coating materials [2]. Despite these advantages, it is generally admitted that the paint surfaces will not achieve the required performance during their SL, which is usually related to several origin effects that can control their service life, like the environmental and climate conditions, the maintenance and reparation defects, etc. [3,4]. Moreover, a good precision for developing different methodologies for the estimation of the service life (ESL) of applied coating is generally correlated to the consideration of these factors. The prediction of SL of any element construction aims to evaluate its performance over time and to predict the required maintenance necessary to repair the defects formed during its SL. Thus, there are several investigations and research studies on relationship between the degradation severity and different deterioration agents using the most recently developed statistical methods for the analysis, and the translation of the durability evolution and modeling of the degradation mechanism occurred at the paint surface [5,6]. Three categories are considered for these methods, namely: methods and durability design standards applied for the ESL, methods for the time-variant structural reliability, and maintenance optimization. According to the first methodology, the ESL can be estimated using different models like deterministic (regression analysis), stochastic, computational, and factorial methods [7]. Among these methods, the deterministic models based on the MLR analysis provide good precision for the ESL of paint coating applied to the external wall of the building [3].

Teo et al. [8] developed a quantitative model for the evaluation and optimization of effective management of maintenance costs necessary for repairing paint coatings applied to the exterior facades of buildings. Visual inspections were carried out to collect different information related to the various deteriorations that occurred during the SL of coating applied to the external facades of social buildings located in Singapore. The collected data during the fieldwork was used to develop a statistical model for different anomalies repaired to predict their appearance and propagation over time. Moreover, the shape of detected anomalies on the building element/system is determined in this work. The validation tests concluded in this study that the model obtained has good significance. On the other hand, Garrido et al. [9] proposed a procedure for the ESL based on the statistical analysis of collected information about the most degradation that occurred on the exterior facades of investigated buildings during their SL. In this work, the deterministic analysis is used to analyze and describe the degradation curves. The authors indicate in this study that this statistical method mainly needs the quantification of the different anomalies detected for the ESL of paint coatings applied on the exterior facades of old buildings. In addition, five degradation agents are considered in this work, namely, the thickness of the coating, the type of paint binder, the texture of the painted surface, substrate preparation, and solar orientation. The data was collected from 100 investigated buildings, and the peeling degradation is considered the most common coating defect. The most results obtained in this investigation work concluded that the methodology assumed gives good results for ESL of external facade painting and also supports the cost estimation for the suitable maintenance approach.

Chai et al. [10] estimated in their work the SL of paint coatings via the data collection of 220 facades located in the Lisbon region in Portugal. Based on the obtained results in this investigation, it appears that the paint coating has several characteristics that mainly affect its durability. They suggested that these factors can be organized into three groups according to their dependence on the quality of materials used, the quality of workmanship, and the environmental exposure conditions. Therefore, the main considered factors in this work that have an important effect on the durability of the studied coating are (i) the age of the paint coating, ii) the paint surface texture, (iii) the distance from the sea, (iv) wind and rain combined action, and (v) the facade orientations. Another study was conducted by Chai et al. [11] to develop a statistical approach for the prediction of the SL of the paint coating of the building envelope. This investigation work is based on the collection of field data via the examination of the state of degradation of 220 paint coatings that were applied to 160 buildings of different construction categories. A mathematical model was defined during this study by the application of MLR analysis, which allows the expressions of the degradation of the studied coating over time as a function of different degradation agents. The authors indicate in this work that the most degradation agents that have an important effect on the deterioration of paint coating are humidity exposure, wind and rain actions, the distance from the sea, the facades' orientations, and the paint finish. As a result of these investigations, the degradation agents indicated that 83% of different anomalies that occurred can be described by three independent variables via the model obtained by an MLR analysis with a significance threshold of 10%, classified as follows: the age of the paint coating, facade orientations, and the distance from the sea.

Silva et al. [3] proposed a procedure for the evolution of the SL of painted coating applied to the exterior facades by examining the degradation state of 220 facades of buildings located in the Lisbon region, Portugal [3]. The effect of different characteristics of the studied coating and their environment on the durability of the materials is also analyzed in this work. In this case, three statistical tools were used during this work: i) simple regression analysis based on the graphical method; ii) MLR analysis; and iii) the ANN method. Mathematical models are generally used for the estimation of the deterioration level of the considered coating as well as to predict its SL. Among these three methods used in this study, it was found that the MLR analysis gives a good result for the prediction of the SL of paint coatings. Indeed, an estimation of 8.5 years ± 0.54 years.

The methodology established in this work for the ESL of external wall painting is based on the inspection of the degradation level of 45 samples located in Algiers, Algeria. In addition, a numerical index (Sw) is calculated for the estimation of the global degradation of each inspected paint coating. The effects of three degradation agents on the paint coating are considered during the inspection work, namely, the age of the paint coating, the distance from the coastal zone, and the solar orientation of the facade. The MLR analysis is used as a deterministic method for the ESL of investigated coatings applied on the exterior walls of Algiers buildings. The performance of the obtained statistical model in this work was examined by the prediction of different surface paints of external walls of buildings located in Algiers.

Materials and methods

Investigation sites

During this work, the data collection was performed from 45 external facades of residential buildings situated in 22 municipalities of Algiers, Algeria (Fig.1). In addition, three independent variables are considered

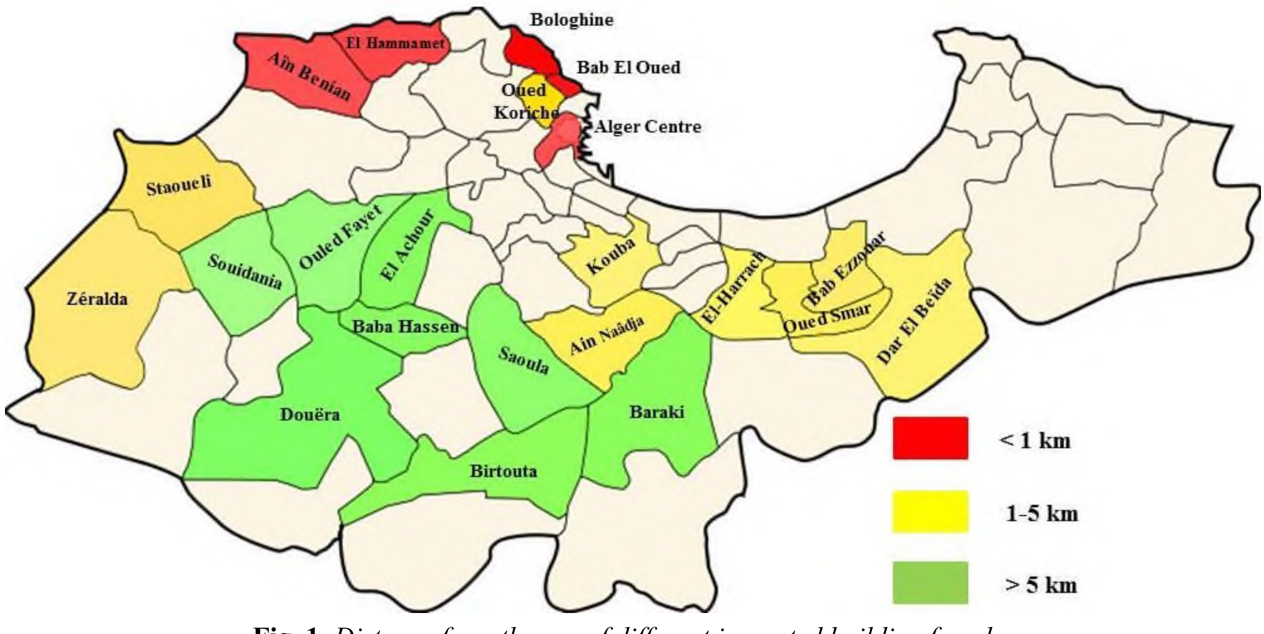

Fig. 1. *Distance from the sea of different inspected building facades*

in this investigation, namely, the age of the paint coating, the distance from the coastal zone, and the solar orientations of facades. The coating ages of inspected building facades in this study are between 3 and 42 years old, as listed in Table 1. Moreover, three categories of coated facades are studied by their distance from the coastal zone in order to evaluate andunderstand the effect of the distance from the sea

Table 1. Distribution of coating ages of different inspected surface paints

Ages of paint coatings (years)	Investigated samples (%)
Under 10	35.56
Between 11 and 20	35.56
Above 21	28.88

on the degradation severity of studied coatings. Practically, for this parameter, the distances are gathered into three categories for the external facades of buildings located: (a) > 5 km; (b) 1-5 km; and (c) < 1 km. The Google Maps application is used in this study for the identification of the orientation of the different facades by considering eight orientations of the facade building: West (W), South (S), East (E), North (N), North/West (N/W), South/West (S/W), South/East (S/E), and North/East (N/E) (Table 2).

For the assessment of the performance of the statistical model derived in this study, six (06) painted surfaces of residential buildings were inspected in Algiers (Table 3). The sampling was carried out by taking into account the three parameters, namely, the coating age, the distance from the coastal zone, and the solar orientations of the facade.

Table 2. Facade orientations versus the number of investigated samples

Facade orientations	Investigated facades (%)
N	13.33
E	8.89
W	24.44
S	24.44
N/E	8.89
S/E	8.89
S/W	6.66
N/W	4.44

Table 3. General information about the investigated samples

Investigated sites		Distance from the sea			
Site localizations	Abbreviations	Real distance from the sea (km)	Categories	Coating age	Facade Orientation
Cité Rue Amar Hamiti-Hussein Dey	CRAH	0.64	< 1 km	≈ 1980	S/E
Cité fico 241 logts-El Magharia	CFEM	1.28	1-5 km	2018	S/E
Cité 118 logts-El Magharia	CLEM	1.36		2018	E
700 logts-Bentalha-Baraki	LBB 1	11.51	> 5 km	2013	W
700 logts-Bentalha-Baraki	LBB 2	11.51		2013	N
700 logts-Bentalha-Baraki	LBB 3	11.47		2013	E

The field work description

Different methods and tools are used for the collection of data during the fieldwork, the methodology is described as follows: (i) taking photos of different targeted facades; (ii) measuring of facade dimensions; (iii) collecting from local administration (OPGI, Office de Promotion et de Gestion Immobilière) different information about the first and the last retrofitting operation; (iv) on-site identification and analysis of applied painting facades; and finally (v) completing of inspection form established for each inspected facade. The independent variable of "age coating" is defined as the time separating the date of the last painting with total or partial reparation of the paint coating and the inspection date. Based on the OPGI's technical documents, the acrylic paint coating is applied to all inspected facades. On the other hand, the effect of four degradation agents on the degradation severity of paint surfaces is studied during this work, i.e., color change (CC), chalking (CG), cracking (CK), and loss of adherence (LA). Thus, the estimation of the degradation level of each considered anomaly is established according to its corresponding international standards (Table 4).

Table 4. Studied anomalies with corresponding international standards

Anomalies	Standards	
CC	ISO 3668[1] and ISO 4628-1[2]	
CG	ISO 4628-6[3] and ISO 4628-7[4]	
CK	ISO 4628-4[5]	
LA	Blistering	ISO 4628-2[6]
	Peeling	ISO 4628-5[7]

Degradation severity

A mathematical expression is generally applied to explain the overall degradation observed at different inspected paint surfaces by using the different information and data collected during the fieldwork. A group of authors established a numerical index for the quantification of the global deteriorations that occurred during the SL of building materials [12,13]. This numerical index (Sw), which translates the degradation severity, is described in (1).

$$S_w = \frac{\sum(A_n \cdot k_n \cdot k_{a,n})}{At \cdot k} \cdot 100\,, \tag{1}$$

where *Sw* represents the degradation severity of analyzed materials (%); k_n is the multiplying factor of defects n, $k_n = \{0, 1, 2, 3, 4\}$; $k_{a,n}$ is the weighting coefficient explaining the relative weight of each considered degradation ($k_{a,n} \in R^+$); $k_{a,n} = 1$ by default; A_n is the area of paint surfaces affected by the degradation n (m^2); *A* is the global facade area, (m^2) and *k* represents the multiplying factor translating the maximum deterioration level of the studied coating with area A. In this work, the evolution of the multiplying factor (k) indicates the degradation levels on the SL of the considered materials. As a result, five degradation levels noted: A, B, C, D, and E are considered in this work for k values.

The different anomalies detected on the inspected painted surfaces do not all have the same relative importance on the overall degradation of this coating. For this purpose, the analysis of the relationship between the anomalies, their causes, and the consequences on the performance of the system becomes fundamental to evaluate the influence of the stages of production on the appearance of the anomalies and on the performance of the paint coating systems. Based on the study performed by Bauer et al. [6], the relative importance (weighting factor) of each anomaly detected in the coating surface can be translated by the calculation of a coefficient obtained through correlation matrices. These matrices are scored with values of 0 (no relationship),

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[1] ISO 3668, Paints and varnishes — Visual comparison of the colour of paints, Draft International Standard, 44 (2017).

[2] ISO/DIS 4628-1, Paints and varnishes — Evaluation of degradation of coatings — Designation of quantity and size of defects, and of intensity of uniform changes in appearance —Part 1: General introduction and designation system, Draft International Standard, 44 (2016).

[3] ISO 4628-6, Paints and varnishes — Evaluation of degradation of coatings — Designation of quantity and size of defects, and of intensity of uniform changes in appearance — Part 6: Assessment of degree of chalking by tape method, BSI Standards Publication, (2011).

[4] ISO 4628-7, Paints and varnishes — Evaluation of degradation of coatings — Designation of quantity and size of defects, and of intensity of uniform changes in appearance — Part 7: Assessment of degree of chalking by velvet method, 2016.

[5] ISO 4628-4, Paints and varnishes — Evaluation of degradation of coatings — Designation of quantity and size of defects, and of intensity of uniform changes in appearance — Part 4: Assessment of degree of cracking, Draft International Standard, 44 (2016).

[6] ISO 4628-2, Paints and varnishes — Evaluation of degradation of coatings — Designation of quantity and size of defects, and of intensity of uniform changes in appearance — Part 2: Assessment of degree of blistering, Draft International Standard, 44 (2016).

[7] ISO/DIS 4628-5, Paints and varnishes — Evaluation of degradation of coatings — Designation of quantity and size of defects, and of intensity of uniform changes in appearance — Part 5: Assessment of degree of flaking, Draft International Standard, 44 (2016).

1 (low relationship), or 2 (strong relationship). As a result, the weighting coefficient ($k_{a,n}$) can be calculated by the ratio of the product between the cause indicator and the performance indicator and the normalization of the maximum value of the product between the performance indicator and the cause indicator, according to (2).

$$k_{a,n} = \frac{I_c \cdot I_p}{max(I_c \cdot I_p)}, \quad (2)$$

where $k_{a,n}$ is the weighting coefficient; I_c is the importance index related to the causes of each anomaly; I_p is the relative importance index of each anomaly in the facade of loss performance. More details about these two indicators are given in the following paragraphs.

In this work, different causes or effects on the service life of painted surfaces are classified into four main groups namely, Materials' characteristics, Design factors, Environmental and exposure conditions, and Maintenance. This classification is established based on the study of Chai. et al. [11].

The importance of the relation between cause and pathology is evaluated using indices to designate a possible correlation. The value of the correlation index is as follows: 2 for a strong relation, 1 for a possible relation, and 0 when there is no relation between the causes and pathologies. The relevance of each pathology is measured by an importance index related to the causes (*Ic*), described by (3). This index evaluates the importance of the causes of several studied pathologies.

$$I_C = \frac{\sum_{i=1}^{N} \mu_{ci}}{\mu_{c\,tot}} \quad , \quad (3)$$

where I_c is the importance index related to the causes of a pathology, N is the number of groups analyzed (Materials' characteristics, Design factors, Environmental and exposure conditions, and Maintenance; in this case N = 4), μ_{ci} is the mean of the correlation indices for the causes of a pathology in each group analyzed, and μ_{ctot} is the sum of all μ_{ci} values for all anomalies (color change, chalking, cracking, and loss of adherence).

For the determination of the performance loss index (I_p), the correlation of the anomalies with the loss of performance of the building facade is analyzed. The anomalies are then classified based on their influence on the performance decrease into three groups: structural, watertightness, and aesthetics, where the same correlation indices are chosen (2 for a strong relation, 1 for a possible relation, and 0 when there is no relation). For each anomaly, the sum of the correlation indices in the three performance groups is made. Through this method, it can be compared how much each anomaly affects the performance loss. The relative importance index of different studied anomalies in the facade loss of performance (*Ip*) is calculated by (4).

$$I_p = \frac{P_{ki}}{P_{k\,total}}, \quad (4)$$

where *Ip* is the relative importance index of an anomaly i in facade loss of performance, N is the number of anomalies (in this case N = 8), P_{ki} is the index of loss of performance of an anomaly I (sum of the correlation indices for each pathology), $P_{k\,total}$ is the sum of the values of p_{ki}, considering all considered anomalies detected in painted surfaces.

MLR analysis

To investigate the relationship among the different factors and the dependent variable, the MLR analysis is one of the most statistical methods that is usually applied in this field. Indeed, for any application of MLR in ESL, the main objective is generally to explain a specific reality and try to predict the variation of dependent variable values (Sw) versus the independent variables. Equation 5 gives the general mathematical formula used in MLR analysis.

$$Y_i = b_0 + b_1X_1 + b_2X_2 + \cdots + b_iX_i + \varepsilon_i = \sum_{i=1}^{p} = b_iX_i + \varepsilon_i \ , \quad (5)$$

where Y represents the dependent variable, Xi values are the independent variables, bi values are the coefficient parameters of the obtained model, and ε_i is the model's random error. The MLR analysis is performed with SPSS software and Microsoft Excel during this work.

Results and Discussion

Quantification of degradation factors

The estimation of the service life of each building material using the MLR analysis generally requires the quantification of the considered qualitative factors by the graphical method. According to this method, both simple linear and nonlinear regression models can be established depending on the considered factors that strongly affect the sustainability of paint coatings. Thus, three characteristics are considered during this work: the coating age, distance from the sea, and facade orientations. The relationship between Sw and the age of the different inspected paint coatings can be translated by different regression analyses of linear, quadratic, cubic, exponential, and logarithmic methods. Therefore, this approach was applied in this work for the estimation of the reference service life (RSL) of inspected external wall painting (45 samples) after the quantification of two independent variables, the distance from the sea and the facade orientation. It consists of adjusting a simple linear regression line with a dispersion of different points plotted in two dimensions; the X axis indicates the variation of the "age variable", and the Y axis corresponds to the values of the severity of degradation index (Sw). The coefficient of determination (R^2) indicates the percentage of variance of the dependent variable of Sw. The mathematical model was obtained using a graphical method based on simple linear regression analysis of the relationship between the values of the Sw and the inspected paint coating ages.

Before the estimation of the RSL and the quantification of the qualitative independent variables, the degradation level must be defined for each type of anomaly according to its characteristics. However, there are different possible degradation defects on the paint surface, due to the combination effect occurring between various degradation agents and mechanisms. In general, the deterioration level is mainly explained by the distribution degree of the anomaly on the facade coating. For this purpose, various investigations were carried out in order to implement a classification system of different anomalies detected in the paint surface to express the physical and performance loss of the building facade [14-16]. Based on these studies, the authors define five levels, which clearly explain the severity of paint degradations, from 0 to 4, where 0 corresponds to no significant degradation and 4 to strong degradation. As indicated in Table 5, the degradation levels are regrouped depending on the severity values. Level 3 is defined as the limit SL of the painted surface, which corresponds to the Sw values ≥ 20%.

The RSL of investigated paint surfaces is obtained using a simple regression analysis, in which a trendline is adjusted to the scatter plot established for Sw values and the age of the coating, Y and X axes, respectively (Fig.2). Indeed, two trendlines were applied, namely linear and second-degree polynomial regressions, which are adjusted to the scatter plot obtained via data collected during the fieldwork. The respective equations and the coefficient of determination obtained by the two models are also presented in this Figure. The linear and nonlinear (polynomial) models show values of R^2 equal to -0.473 and 0.304, respectively. These values highlight that the tendency of degradation severity results as a function of coating age can be explained by a second-degree polynomial curve.

Table 5. Relationship between severity values and degradation levels [4]

Severity index	Degradation levels
$S_w < 1$ %	0
1% $< S_w <$ 10 %	1
10 % $< S_w <$ 20 %	2
20 % $< S_w <$ 40 %	3
$S_w >$ 40 %	4

Indeed, 30.44% of the degradation severity can be explained by this trend line by considering the age of the coating as the only explanatory variable. This result deduced from the second- degree polynomial model does not give a high precision of the degradation process of painted surfaces because the severity of degradation is not well correlated with the age of the coating system. This is probably due to the degradation process, which does not occur at the same rate over time. Thus, the degradation initially occurred at a slower rate, tending to accelerate at the end of the SL of painted surfaces; moreover, it can be due to the degradation process, which does not depend exclusively on the age of the buildings, being impacted by several reasons, as previously indicated in this study.

The RSL was also deduced from this graphical analysis. As a result, the average expected SL for all inspected externally painted surfaces is obtained by the intersection between the trend curve and the degradation severity of 20%. As shown in Fig. 2 and Table 5, the RSL obtained is 20.3 years. This result is higher than the RSL found in the literature; using the graphical method, Chai et al. [11] obtained an RSL value of 9.6 years with a paint coating number of 220 samples. Moreover, Magos et al. [4] deduced an RSL of 10.8 years; a variation of 10% compared to the value found by Chai et al. [11] is obtained with a larger number of facades (323 paint coatings). This result confirms that the number of samples studied has a significant effect on the determination of RSL by this graphical method. As a result, the second point of intersection between the two lines is due to the existence of outliers in the age interval of the coating between 35 and 40 years.

The analysis of the degradation curves of Sw values as a function of the coatings' age can also lead to the estimation of the SL of painted surfaces according to each studied characteristic (Table 5, Figs. 3,4). In this work, the Sw values of the two qualitative variables, namely the distance from the sea and the facade orientation, are considered for this analysis. Simple linear and nonlinear (polynomial) regression analysis was adjusted to different points of the graphs of the two studied variables, distance from the sea and facade orientation. The ESL of studied groups of paint coating samples with a specific independent variable is established through the intersection that occurred between each degradation curve and the severity level of 20% (Figs. 3,4).

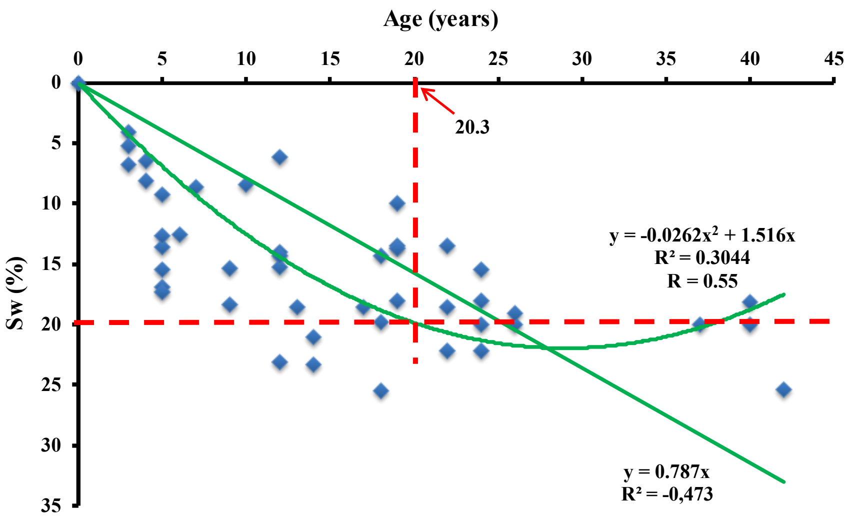


Fig. 2. *Estimation of the RSL of the investigated paint coating*

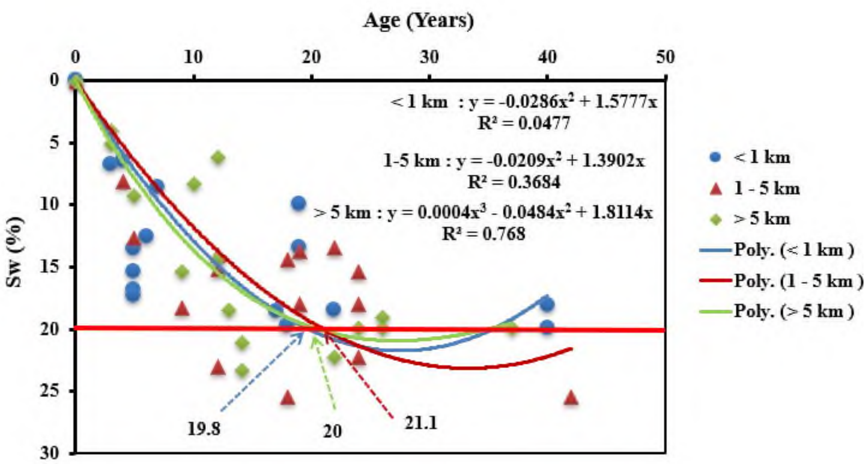


Fig. 3. *Severity index as a function of distance from the sea*

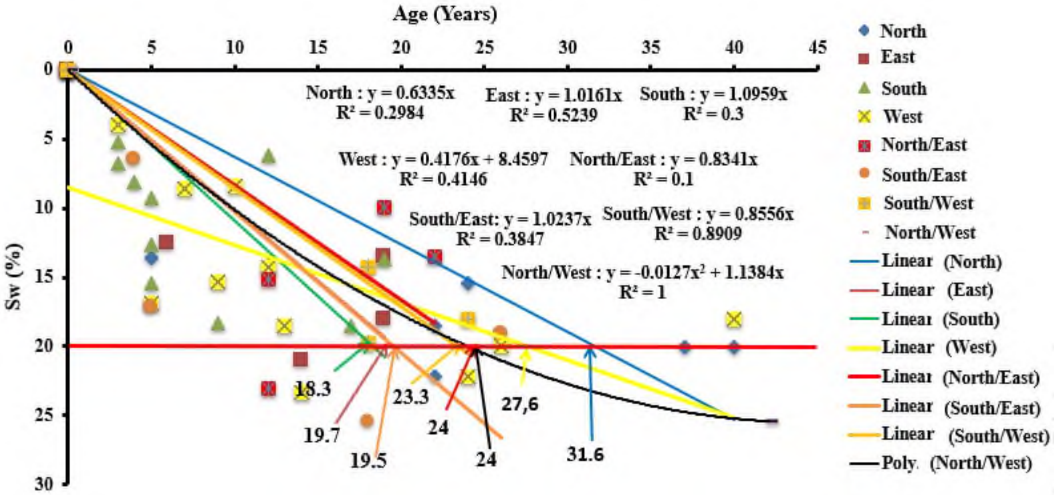


Fig. 4. *Severity index versus facade orientations*

The quantification of the qualitative variables is required before using the MLR analysis. In this study, each group of anomalies was expressed by the value that represents the ratio between the estimated service life (ESL) based on each coating characteristic and the RSL of 20.3 years (Table 5). The results shown in Table 5 indicate clearly that the distance from the sea significantly affects the SL of paint coatings. As a result of this, an ESL of 19.8 years was obtained for painted surfaces located within less than 1 km of the coastal zone. This estimation is less than 1.3 years compared to the facades located at distances from the sea more than 1 km, which is mainly due to the strong exposure of these paint surfaces to the high salinity of sea spray and humidity, which leads to the crystallization of salts at internal and external surfaces of studied coatings. This phenomenon mainly causes the formation of various damages at an early age, such as blisters, loss of adhesion, color change, biological colonization, etc. [17].

Moreover, Fig. 4 and Table 6 indicate that all facades oriented to the south, east, and south/east have a slightly lower SL compared to the other orientations. This result is mainly due to the high exposition of these facades to the solar radiation, which involves the development of different anomalies related to the sun exposure, such as color change, cracking, chalking, etc. However, this analysis indicates that the most favorable orientations regarding the durability of this type of coating for exterior facades of buildings in the Algiers region are north and west orientations. This result indicates the highest service life estimation of 31.6 and 27.6 years, respectively, for the north and west orientations.

Table 6. Quantification of qualitative independent variables

Characteristics	Independent variables	% of cases	RSL (years)	ESL (years)	Ratio between ESL and RSL	R^2 of degradation curves
Distance from the sea	< 1 km	33.33	20.3	19.8	0.975	0.0477
	1 – 5 km	33.33		21.1	1.039	0.3684
	> 5 km	33.33		20	0.985	0.768
Facade orientation	N	13.33		31.6	1.556	0.2984
	E	8.89		19.7	0.970	0.5239
	S	24.44		18.3	0.901	0.3
	W	24.44		27.6	1.359	0.4146
	N/E	8.89		24	1.182	0.1
	S/E	8.89		19.5	0.960	0.3847
	S/W	6.66		23.3	1.147	0.8909
	N/W	4.44		24	1.182	1

Mathematical model of Service life prediction

Regression analysis is one of the statistical techniques widely applied for studying the effect of one or several independent variables on the variation values of dependent variables, which are responsible for its performance. According to the results obtained by the two software programs, EXCEL and SPSS, the relationship between Sw values (variable Y) and the three considered independent variables, namely, coating age (CA), distance from the coastal zone (DS), and facade orientations (FO), is given in (6) and (7).

$$Y = -0.22 + 0.003\ (X_1) + 0.305\ (X_2) + 0.021\ (X_3). \quad (6)$$

$$S_w = -0.22 + 0.003\ (CA) + 0.305\ (DS) + 0.021\ (DO). \quad (7)$$

It should be noted from both (3) and (4) that the value of each coefficient translates the importance of the adequate independent variables in the prediction of dependent variable values. Indeed, the coefficient of the coating age variable is positive in the model; as a result, the degradation severity increases significantly with increasing its values. In the case of the other variables, distance from the sea and the facades' orientations, their coefficients are also positive but with a low effect on the variability of Sw values; a variation around 0.5 is estimated.

On the other hand, in the case of each coating sample and for a Sw level of 20%, the estimation of service life can be obtained using (8), where the coating age is considered as the dependent variable.

$$\text{ESL} = \frac{(0.2 + 0.22 - 0.305\ (DS) - 0.021(FO))}{0.003}. \quad (8)$$

Based on the quantification results of independent variables (shown in Table 6), the age of paint surfaces can be estimated for a 20% degradation severity. The ESL is deduced using (8); therefore, the average of all ESL values is calculated for each observation. In addition, the standard deviation of the RSL can also be determined by this method. As a result, the ESL is around 29.9 ± 3.26 years. This estimation is obtained based on degradation severity data in the range of 4-25%, and the age of the coating is between 3 to 40 years. Figures 5 and 6 translate the correlation between the experimental and the estimated values of the severity index Sw. Fig. 6 indicates that a high correlation is obtained between predicted values calculated using (4).

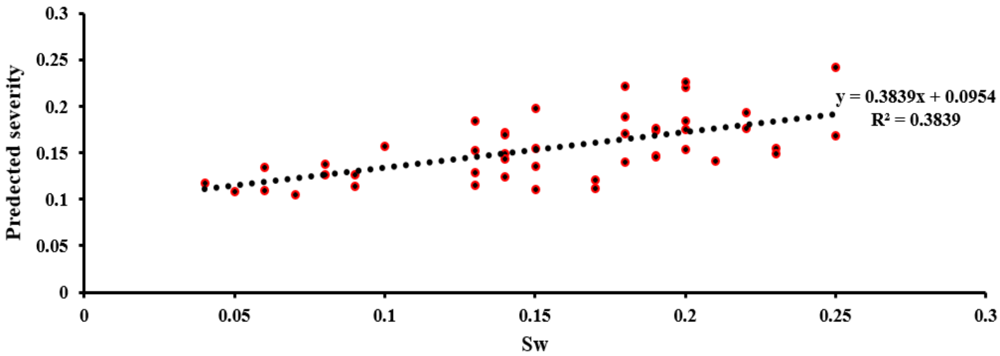


Fig. 5. *Correlation between predicted and experimental severity index*

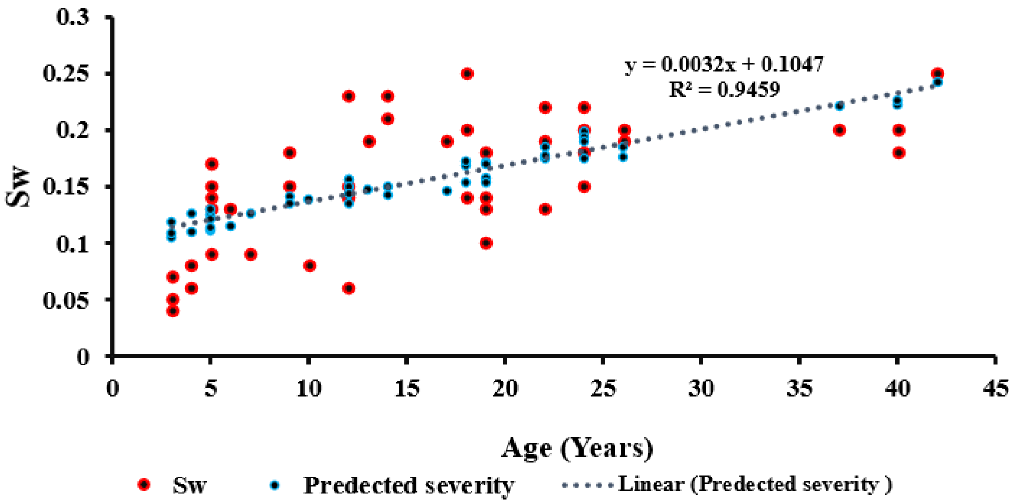


Fig. 6. *Experimental and predicted values of Sw as a function of coating age*

Performance testing of model

The prediction of the SL of six painted surfaces applied to the external walls of selected Algiers building envelopes is investigated for the evaluation of the performance of the SL prediction of the mathematical model obtained via the MLR analysis (Table 7). The statistical investigation for studying the validation of the statistical performance of the mathematical model obtained in this work is conducted by Hammas et al. [18]. As a result, the ESL deduced from the proposed model in this study for all inspected painted surfaces is in accordance with the real ages declared by OPGI. This reflects the good performance of this model in the intervals of coating age and degradation severity studied, 3-40 years and 4-25%, respectively. An example of the calculation method of Sw is indicated in (9) for the LBB 3 coating sample. In addition, the results illustrated in Table 7 also indicate that the prediction of the age of the coating strongly depends on the distance from the sea and the orientation of the facade. An increase in the predicted age from 8.03 to 13.4 years is noted for the two facades, LBB 2 and LBB 3, facing north and east, respectively, which have the same distance from the sea and the same age. This result is in agreement with the conclusions obtained by the graphical study used for the quantification of qualitative independent variables.

$$S_w = \frac{\sum\left(A_n \cdot k_n \cdot k_{a,n}\right)}{At \cdot k} \cdot 100 =$$

$$= \frac{\left(A_{CC} \cdot k_{CC} \cdot k_{a,n(CC)}\right) + \left(A_{CG} \cdot k_{CG} \cdot k_{a,n(CG)}\right) + \left(A_{CK} \cdot k_{CK} \cdot k_{a,n(CK)}\right) + \left(A_B \cdot k_B \cdot k_{a,n(B)}\right) + \left(A_P . k_P \cdot k_{a,n(P)}\right)}{At * k} \cdot 100 = \quad (9)$$

$$= \frac{(107.05 \cdot 1 \cdot 0.55)+(107.05 \cdot 2 \cdot 0.6)+(0.015 \cdot 2 \cdot 1)+(107.05 \cdot 2 \cdot 0,8)+(8.02 \cdot 3 \cdot 0.8)}{267.62 \cdot 10} \cdot 100 = 14.12\ \%.$$

Table 7. Comparative study between the performance service life prediction obtained using the mathematical model obtained in this work and Chai et al. [11]

Paint coating samples	Distance from the sea	Facade orientations	Sw (%)	Real age (ans)	Service life prediction $\pm$ 3.26 ans [a]	Service life prediction $\pm$ 0.54 ans [b]
CRAH	< 1 km	Sud/Est	22.193	**43**	**41.46**	**x**
CFEM	1-5 km	Sud/Est	12.79	**5**	**3**	**x**
CLEM		Est	12.961		**4.11**	**7.29**
LBB 1	> 5 km	Ouest	13.846	**10**	**9.85**	**7.20**
LBB 2		Nord	13.722		**8.03**	**8.14**
LBB 3		Est	14.121		**13.4**	**8.16**

x: Orientation facades were not considered by the investigation work of Chai et al. [11].
[a] Coating age predicted using the mathematical model obtained in this study.
[b] Coating age predicted using the mathematical model obtained by Chai et al. [11].
Green color: The SL prediction is near the real age of the inspected paint coating.
Red color: The SL prediction is far from the real age of the inspected paint coating.

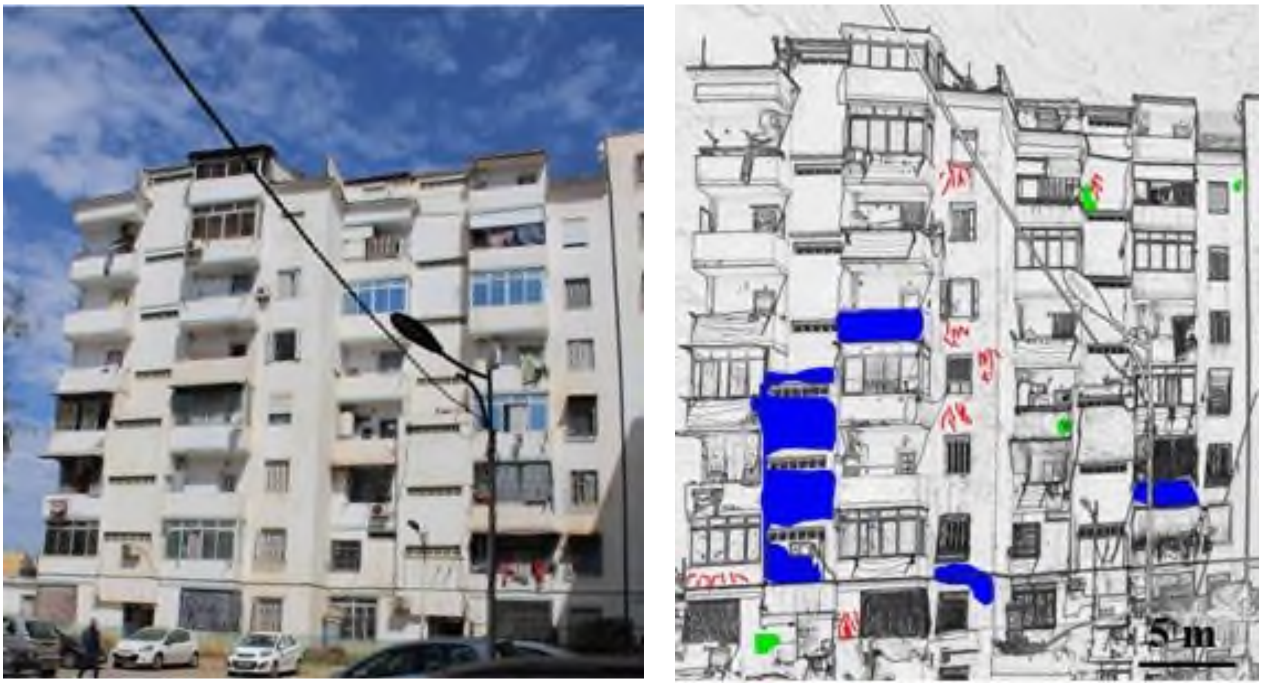
On the other hand, a comparative study is established between the performance of service life prediction calculated using the mathematical model obtained in this work and the model proposed by Chai et al. [11]. Table 7 indicates clearly that the statistical model obtained during this study gives a better precision than the literature model established by Chai et al. [11] for some paint coatings of building envelopes. Moreover, it can be noted that the MLR model developed by Chai et al. [11] has a certain limit for the prediction of aged coatings higher than 30 years. Over this limit of age, the values of Sw are equal to 100%. In contrast, the statistical model obtained during this work can be used for the estimation of the SL of paint coatings aged for more than 30 years, as indicated in the case of the paint coating of the CRAH building facade. The comparison between the performance of both developed MLR models concluded that the obtained model during this study gives good precision despite the moderate quantity of investigated paint coating (45 building facades). To emphasize that performance, the values of the service life predictions close to the real age of the paint surfaces are colored in green in Table 7.

In order to elaborate on the relationship between the detected degradation and the calculated Sw values, different presentations of images are presented with mapping of detected anomalies that were observed at different investigated surfaces of paint applied to the external walls. The three anomalies are mapped, namely color change, cracking, and loss of adherence (Fig.7). The alignment of the different images with their maps was carried out using the two software programs Photoshop and Paint.

It can be seen that the three considered factors have a significant effect on the degradation severity, namely, the coating age, the distance from the sea, and the facades' orientations. Moreover, according to the degradation mapping illustrated in Fig.7, the formation of loss of adhesion (peeling) and color change on the painted surfaces of the exterior facades of buildings is strongly related to the orientation of the buildings. Indeed, more intense peeling degradation is detectable on the painted surface of LBB 3 facades that are 10 year old, facing east and present a degradation severity of 14.121% (Fig.7f). This result is in agreement with the prediction results obtained for the coating age of the different degradation severity which increase on the facades oriented to the East, South, and South/East.

Fig. 7. *Mapping of detected anomalies at different inspected surfaces paints:*
(a) *CRAH,* (b) *CFEM,* (c) *CLEM,* (d) *LBB 1,* (e) *LBB 2,* (f) *LBB 3*

Fig. 7 (continued)



(b)

Color change Loss of adherence Cracking

(c)

Color change Loss of adherence Cracking

Fig. 7 (continued)

(d)

Color change Loss of adherence Cracking

(e)

Color change Loss of adherence Cracking

Fig. 7 (continued)

(f)

Color change Loss of adherence Cracking

Conclusion

In this work, the prediction of the SL of external wall paintings is established using regression analysis based on linear and multilinear regression. A statistical method is used to analyze 45 painted surfaces of external walls of residential buildings located in Algiers. The methodology to assess the SL of coatings is based principally on the visual evaluation of different forms of degradation. The visual evaluation is treated to extract quantification data, and the results are translated into a mathematical model. The combination of the data collected with the anomalies detected in in-service conditions was expressed as numerical values using the graphical method. In addition, the mathematical model is established in this study by relating the degradation severity and the three independent variables, namely, the coating age, the distance from the coastal zone, and the solar orientation facade. According to the results obtained during this study, the following conclusions can be drawn:

- RSL of 20.3 years of studied coating is obtained using the simple linear regression analysis (graphical method).
- Based on the parameters of the model, the SL of paint coating applied to the external wall of the Algiers building depends strongly on the distance from the sea and facade orientations. The lowest ESL of 19.8 years was obtained for an external facade building situated near the coastal zone, and for facades facing east, south, and east/south, 19.7, 18.3, and 19.5 years, respectively.
- For 20% of degradation severity, the ESL of 29.9 ± 3.26 years is obtained from the average of all ESL for investigated paint surfaces, which presents a degradation severity and coating age between 4 and 25% and 3 and 40 years, respectively. It appears that the ESL is consistent with empirical data related to the durability of paint coating, which can also be deduced via this model, even for values beyond 25% in terms of overall deterioration of the considered coating, which is not the case on the models consulted in the literature.
- The comparison study between the MLR model obtained during this work and the developed model in the previous investigations about the ESL of paint coating concluded that a good precision has been attained on the estimation of the SL of six other paint surfaces, which present deterioration severities in the range of 4 and 25%.

Conflict of Interest

The authors declare no conflicts of interest.

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References

[1]. J. Barrelas, A. Silva, J. de Brito, A. Tadeu, Influence of Temperature Increase and Precipitation Decrease on the Degradation Evolution of Rendered Façades in Service Conditions. Journal of Building Engineering, 94, 2024, 109843. Doi: https://doi.org/10.1016/j.jobe.2024.109843

[2]. C.O. Folorunso, M.H. Ahmad, Performance and Resistance of Paint used as Exterior Finish in Salt Laden Environment. Structural Survey, 31(3), 2013, 214-224. Doi: https://doi.org/10.1108/SS-10-2012-0036

[3]. A. Silva, P. Gaspar, J. de Brito, Evaluation of the Service Life of External Painted Surfaces Applying Statistical Tools, in: 1st International Symposium on Building Pathology (ISBP 2015). Porto, Portugal, 2015. http://dx.doi.org/10.13140/RG.2.1.5026.9528

[4]. M. Magos, J. de Brito, P.L. Gaspar, A. Silva, Application of the Factor Method to the Prediction of the Service Life of External Paint Finishes on Façades. Materials and Structures, 49, 2016, 5209-5225. Doi: http://dx.doi.org/10.1617/s11527-016-0855-z

[5]. T.V. Uchaeva, V.I. Loganina, Analysis of the Risk at the Finishing of the Building Products and Construction of Paint Compositions. Case Studies in Construction Materials, 8 (2018) 213-216. Doi: https://doi.org/10.1016/j.cscm.2018.01.001

[6]. E. Bauer, C.B. Piazzarollo, J.S. de Souza, D.G. dos Santos, Relative Importance of Pathologies in the Severity of Facade Degradation. Journal of Building Pathology and Rehabilitation, 5 (7), 2020, 1-10. Doi: https://doi.org/10.1007/s41024-020-0072-6

[7]. A. Silva, J. de Brito, P.L. Gaspar, Comparative Analysis of Service Life Prediction Methods Applied to Rendered Façades. Materials and Structures, 49, 2016, 4893-4910. Doi: https://doi.org/10.1617/s11527-016-0832-6

[8]. E.A. Teo, N. Harikrishna, A Quantitative Model for Efficient Maintenance of Plastered and Painted Facades. Construction Management and Economics, 24 (12), 2006, 1283-1293. Doi: https://doi.org/10.1080/01446190600987704

[9]. M.A. Garrido, P.V Paulo, F.A. Branco, Service Life Prediction of Façade Paint Coatings in Old Buildings. Construction and Building Materials, 29, 2012, 394-402. Doi: https://doi.org/10.1016/j.conbuildmat.2011.10.057

[10]. C. Chai, J. De Brito, P.L. Gaspar, A. Silva, Predicting the Service Life of Exterior Wall Painting: Techno-Economic Analysis of Alternative Maintenance Strategies. Journal of Construction Engineering and Management, 140 (3), 2014, 4013057. Doi: https://doi.org/10.1061/(ASCE)CO.1943-7862.0000812

[11]. C. Chai, J. De Brito, P.L. Gaspar, A. Silva, Statistical Modelling of the Service Life Prediction of Painted Surfaces. International Journal of Strategic Property Management, 19 (2), 2015, 173-185. Doi: https://doi.org/10.3846/1648715X.2015.1031853

[12]. P.L. Gaspar, J. de Brito, Quantifying Environmental Effects on Cement-Rendered Facades: A Comparison between Different Degradation Indicators. Building and Environment, 43 (11), 2008, 1818-1828. Doi: https://doi.org/10.1016/j.buildenv.2007.10.022

[13]. R. Bordalo, J. de Brito, P.L. Gaspar, A. Silva, Service Life Prediction Modelling of Adhesive Ceramic Tiling Systems. Building Research & Information, 39 (1), 2011, 66-78. Doi: https://doi.org/10.1080/09613218.2010.532197

[14]. E. Brandt, M.H. Rasmussen, Assessment of Building Conditions. Energy and Buildings, 34 (2), 2002 121-125. Doi: https://doi.org/10.1016/S0378-7788(01)00102-5

[15]. F. Flourentzou, E. Brandt, C. Wetzel, MEDIC—A Method for Predicting Residual Service Life and Refurbishment Investment Budgets. Energy and Buildings, 31(2), 2000, 167-170. Doi: https://doi.org/10.1016/S0378-7788(99)00031-6

[16]. A. Silva, J. de Brito, P.L. Gaspar, Service Life Prediction Model Applied to Natural Stone Wall Claddings (Directly Adhered to the Substrate). Construction and Building Materials, 25 (9), 2011, 3674-3684. Doi: https://doi.org/10.1016/j.conbuildmat.2011.03.064

[17]. J. Hinks, G. Cook, The Technology of Building Defects. Routledge, London, 2002. Doi: https://doi.org/10.4324/9780203475362

[18]. A. Hammas, A. Brara, Service Life Prediction of Paint Coating of Algiers Building Envelopes by Applying a Multiple Linear Regression Analysis. Proceedings of the International Conference of Contemporary Affairs in Architecture and Urbanism-ICCAUA, 6 (1), 2023, 150-156. Doi: https://doi.org/10.38027/iccaua2023en0255

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CULTURAL INFLUENCES ON ARCHITECTURAL DESIGN IN RWANDA'S URBAN CENTERS

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Abstract: *Rwanda's architectural identity reflects a dynamic blend, for example, the circular forms of inzu huts, colonial influences, for example, Belgian rectangular forms, and contemporary urban aspirations as current as Kigali Vision 2050. This integration of ancient features, e.g., nyakatsi (thatched houses), into modern designs demonstrates a dynamic interaction between past and present life. This paper analyzes the cultural influences on architectural design in urban contexts such as the City of Kigali, concerning how local traditions, building materials, and community requirements influence building activities. The study uses qualitative methods, such as interviews with architects, urban planners, and the community, as well as case studies of exemplary works. Results show a high preference for sustainable materials and designs that tie into Rwandan culture and a strong focus on the engagement of the community in the planning stage. The work further reveals issues of rapid urbanization and modernity vs. traditional tension. Suggestions involve the establishment of policies that protect cultural heritage and accommodate urbanization. This study contributes to the knowledge of the role of cultural representations guiding architectural practices in Rwanda and provides some implications for urban development.*

Keywords: *Architectural design, Rwandan heritage, cultural influences, sustainability, local materials, traditional values, urban centers, innovation, tradition, modernity.*

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Introduction

Rwanda is known as "a land of a thousand hills". The architectural landscape of Rwanda is a confluence of vast and long-standing cultural heritage and rapid socio-economic advancement. With the shift from rural to urban settlements in the course of the country, maintaining a deep cultural identity behind the construction of its architecture is woven through the fabric of society. City centers, such as Kigali, with a development vision 2050 plan[1] [1], have fully embraced city dynamics and are typical examples of a global architectural terminology that can easily dwarf local design principles. In Rwandan architecture, traditional plots and housing plans known as "Inzu" featured a circular shape and used local building materials such as mud, wood, and thatch, and had a conical roof. Both public and common designs and uses were apparent before colonists came. The arrival of European colonists in Germany and Belgium brought new architectural patterns for consideration: buildings and plots having a square or rectangular shape, namely Belgian colonial architecture, inspired by concrete structure and disciplined design [2,3]. Rwandan architecture has traditionally been earthen, environmental, and community-bound.

Traditional homes, such as the nyakatsi, and the intricate patterns found in weaving and crafts, represent not just aesthetic choices but also deeply rooted cultural values. However, the pressures of urban development, globalization, and technological advances present challenges in maintaining these core elements. The architectural typologies of Rwanda are deeply enshrined in their cultural context, which has been formed for centuries due to a process of social and political changes. Traditional Rwandan designs using locally available materials such as mud, wood, and thatch are embodiments of the Rwandan way of life and its social structure.

[1] P. Rubingisa, Kigali Master Plan (Report). Available at: https://surl.lt/gybppr (accessed on October 24, 2023).

Nonetheless, by incorporating areas visited by the 1994 genocide and subsequent reconstruction, the urban fabric was affected, resulting in the mixing of traditional and modern architectural styles[2] [4].

The purpose of this paper is to investigate the cultural impact on architectural design in the Rwandan urban fabric, especially in Kigali, the capital city, where the country's architectural development is a small-scale version. To what degree can cultural factors be responsibly integrated into architectural designs in Rwanda's urban areas? In this respect, the paper also illuminates the broader consequences of the phenomenon of sustainable urbanism and the preservation of cultural heritage in the developing world. The following subsections investigate the cultural, social, and economic factors that have shaped the urban architectural identity of Rwanda and, in detail, explore the issues and opportunities embedded in this endeavor.

Statement and Description of the Problem

Rwanda's urban population is projected to reach 35% by 2050, threatening indigenous designs. In Kigali, 70% of new buildings use imported concrete [5], doubling the carbon footprint of traditional earth bricks (ikibuga). The cities of Kigali, Musanze, Huye, Rubavu, Rusizi, Nyagatare, and Muhanga are growing in size due to population growth and development initiatives, as shown in Figures 1 and 2. This rapid urbanization increases the risk that native architectural designs will be overtaken by globalized trends that have no relevance for the local context.

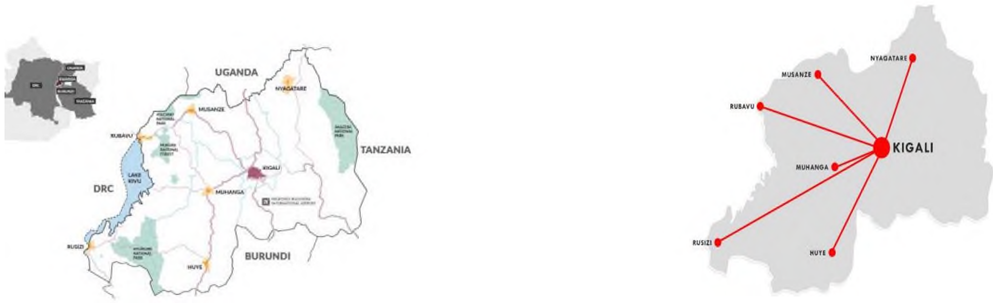

Fig. 1. *Regional plan cities of Rwanda*[3] *[6]*

The challenge is to establish an appropriate equilibrium between modernizing and conserving a robust local identity in the context of Rwandan culture. Whenever there is more foreign capital flow, projects that favor effectiveness over originality arise, leading to architectural forms that are detached from historicity or community identity usage. Additionally, today's designs areoften short-sighted in neglecting the use of locally made materials or traditional building methods, which causes not only aesthetic disconnect but also represents an environmental impact caused by the transportation of materials from distant areas. This article aims to provide insight into how cultural interventions can be incorporated into contemporary architectural design in the interest of harmonious urbanism, respectful of cultural Rwandan heritage.

Fig. 2. *Rapidly urbanizing cities in Rwanda [5]*

[2] R.S. Tours, Exploring Rwanda's Architectural Heritage | Rwanda Safaris. Available at: https://surl.li/tbpodv (accessed on November 20, 2020).

[3] P. Rubingisa, Kigali Master Plan (Report). Available at: https://surl.lt/gybppr (accessed on October 24, 2023).

Cultural and environmental impacts:

- Cultural Impact: If the built environment and cultural narratives are disconnected, disaffiliation occurs, and communal identity is lost.
- Environmental Concerns: Unsustainable industrial consumption of imported concrete and glass results in an increased carbon footprint, whereas the traditional Rwandan construction approach is based on sustainable principles.

Research Methodology

This study employs a mixed-methods approach to examine cultural influences on Rwanda's urban architecture, combining qualitative insights with quantitative spatial analysis. The three-phase methodology was designed to capture both historical traditions and contemporary urban dynamics.

Qualitative Methods

Interviews:

- Conducted 10 semi-structured interviews (2020-2024) with 3 local architects (e.g., Alain Yves Twizeyimana and Emmanuel Havugimana, in Kigali), 4 urban planners (Musanze and Rubavu), and 3 community elders (Nyamirambo, Huye, and Nyanza).
- The objectives were to assess cultural priorities in design choices.

Case studies:

- Analyzed 6 projects that are culturally integrated (Kigali Convention Center, KCC, Nyamirambo Women's Center), globalized (Kigali Heights Mall, Vision City), and of hybrid design (Gacuriro Valley Housing).
- Criteria: use of local materials, community engagement, aesthetic traditions.

Quantitative Methods

GIS mapping of Kigali's urban growth (2010-2023) using:

- Rwanda Land Management and Use Authority base maps,
- High resolution (0.5m) satellite imagery,
- Ground truthing through site visits.

Materials use analysis through:

- Field surveys of 120 buildings across 10 districts,
- Categorization into traditional materials (earth, mud, thatch, stones, and wood), hybrid, and Modern materials,
- Statistical comparison of materials prevalence by construction year. This analysis quantified the shift towards imported materials, revealing that approximately 70% of new buildings in Kigali use imported concrete [5].

Policy and comparative analysis

Document review of the Kigali Master Plan 2020, Rwanda Vision 2050, and National Heritage Preservation Guidelines.

Historical analysis traced the evolution of Rwandan architecture from traditional huts to contemporary urban buildings and compared Rwanda's architectural trends with those of other African nations, such as Kenya, Ethiopia, Tanzania, South Africa, Burkina Faso, and Ghana, which face similar urbanization challenges. Identified best practices for integrating culture into urban design.

Presentation and Discussion of Results

Historical Context and Cultural Foundations

The architectural scene in Rwanda is profoundly shaped by its historical background and cultural roots, especially in the case of cities (e.g., Kigali). The history of architectural design in Rwanda exhibits an integration of traditional knowledge, colonialist design principles, and a late strategy for the planning of cities in accordance with the increasingly rapid urbanization and sustainability of the city.

Historical Context

Pre-Colonial Architecture: Before the arrival of European colonizers, Rwandan architecture was characterized by traditional building techniques that utilized locally available materials. Homes known as inzu huts were typically circular structures that were built using locally sourced materials such as mud, thatch, wood, and stones, reflecting the communal lifestyle and social organization of Rwandan society. For example, the King's Palace in Nyanza (Fig.3) is an introduction to the classic architecture of Rwanda, which is formed of circular houses and is based around what determines the role of the monarchy and the community [7,8] .

Fig. 3. *The King's Palace in Nyanza[4] [7]*

Not only were these structures functional, but they were also symbolic, signifying unity and family bonds. Organisation around spaces common to the village inhabitants of the layout of the Rwandan villages was common and facilitated socialization and cooperation. Forms of architecture were modified according to the local climate, with layouts promoting natural cooling and ventilation. This Indigenous architectural knowledge laid the foundation for future developments in Rwandan urban centers**.**

Colonial Influence: The late 19th and early 20th centuries witnessed a shift in the architectural landscape of Rwanda at the time of the arrival of the German and Belgian colonialists. Colonial architecture introduced European styles, which often disregarded local traditions. Architecture represented by the period of this building, such as administration offices, educational institutions, and churches, in the furniture of rectangular, masonry and elegant facades, represented the buildings of this period. This colonial power trace has not only been physical space redesignated, but, at the same time, it has put new social stratifications into the equation, thereby changing the community structure[5,6]. Through the appearance of Western architectural structures infiltrating the traditional local communities and gradually eroding and spoiling traditional practices, the colonial rulers reinforced their dominance through architecture.

[4] R.S. Tours, Exploring Rwanda's Architectural Heritage | Rwanda Safaris. Available at: https://surl.li/tbpodv (accessed on November 20, 2020).

[5] Rwandan historical architecture and its influence on modern design – Relocation Experts Rwanda Ltd. Available at: https://surl.li/xurhfh (accessed on December 04, 2024).

[6] Rwanda's Radical Transformation Since the End of the 1994 Genocide against the Tutsi. 2023.

Post-Independence Developments: Since 1962, Rwanda's independence triggered interest not only in the recovered and reconstituted cultural identity but also in architecture. The desire to create a national identity led to the revival of traditional architecture and its manifestations. Nevertheless, this period witnessed political upheaval and strife that culminated in the 1994 genocide, which further muddied the picture, as much of the built environment was destroyed, making reconstruction an urgent priority. In the aftermath of the genocide, Rwanda faced the immense task of rebuilding its physical infrastructure while addressing social fractures, emphasizing modern architecture while attempting to incorporate elements of Rwandan culture and identity. Architectural design has become a means to foster reconciliation and healing. Memorials and community centers were constructed to commemorate victims and to cohesively bring survivors' deliverance into a place[7] [5]. The Kigali Genocide Memorial is a paradigmatic example of the role that architecture can occupy at the crossroads between the memorial function and the contribution to national identity construction processes. Hybrid designs (e.g., Kigali Genocide Memorial), as shown in Figure 4, blend tradition with modernity[8].

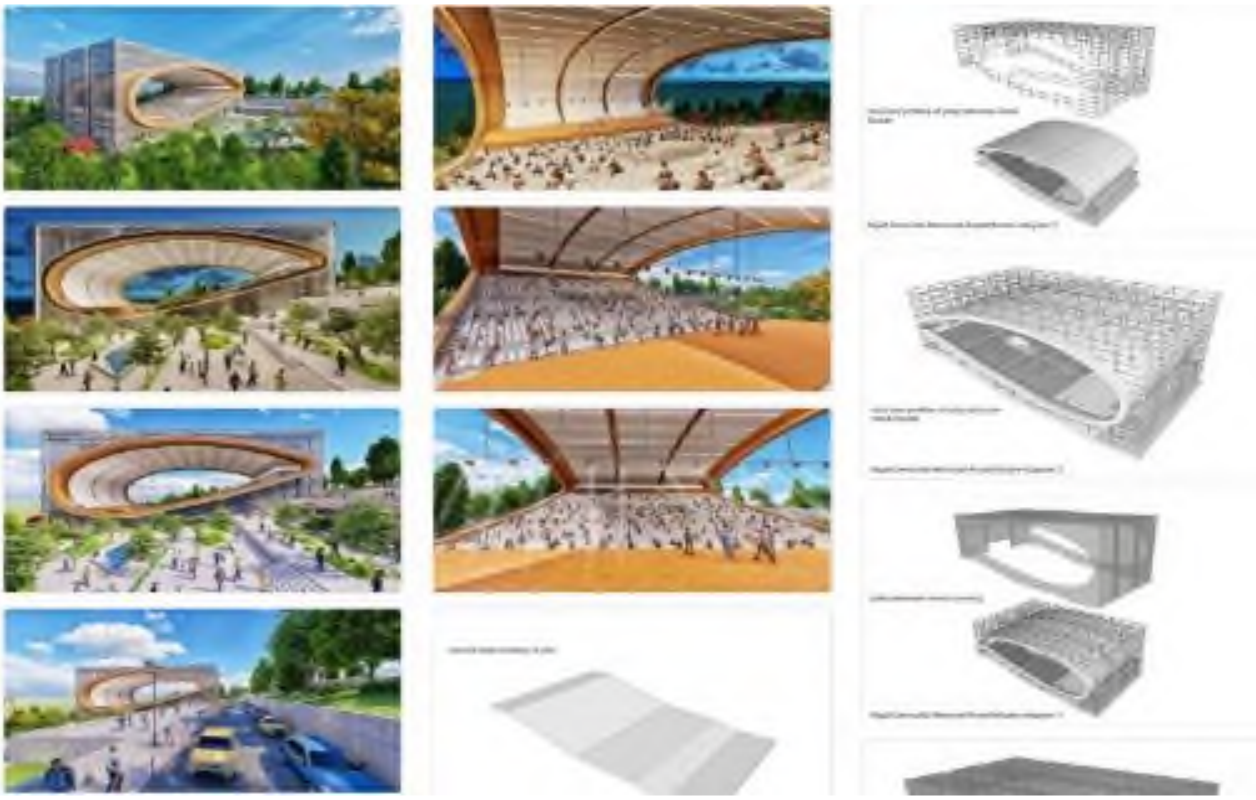

Fig. 4. *The Kigali Genocide Memorial*[9]

Cultural Foundations

Identity and Memory: In Rwanda, cultural identity plays a key role in the direction of architectural design. The introduction of classical elements into modern structures is an expression of a desire to safeguard cultural heritage while also addressing contemporary needs. Architects presently are engaged in a new broad effort of incorporating indigenous materials, forms, and construction practices into their design to construct design spaces that are evocative of Rwandan culture. For example, contemporary public elements often derive inspiration from more traditional examples, such as circular shops and highly decorated patterns like those seen in basket weaves. This meeting of the past and present not only honors traditional narratives but also helps residents feel as if they belong there.

[7] The intersection of contemporary African architecture and art. Available at: https://surl.lt/wxxfjl (accessed on December 04, 2024).

[8] Wall Corporation/Selim Senin - Kigali Genocide Memorial Amphitheatre in a circular void. Available at: https://surl.lu/zccflm (accessed on November 30, 2018).

[9] Ibid.

Community Engagement: Rwandan culture emphasizes communal values and collective decision-making. This cultural background has impacted architectural practices, promoting participation of the community in the design process. Architects are increasingly involved in interacting with local communities on the specification of what the future state of their community will be, in partnership, to provide designs that the community will both support and welcome. An example of this participatory approach is the Nyamirambo Women's Centre (Fig.5). The projects can be seen as providing places both practical and culturally valuable.

Fig. 5. *The Nyamirambo Women's Center*[10]

By embedding communities in the process, architects can create sites that promote social cohesion and pay respect to local culture.

Sustainability Practices: Sustainability has begun to take its place in architectural design in Rwanda, as Rwandan architects try to reduce their environmental footprint while respecting local cultural values. The use of locally sourced materials, such as clay bricks or bamboo, not only promotes sustainability but also reinforces a connection to Rwandan traditions. Architectural firms emphasizing environmentalism represent a maturity of thought on the critical preservation of natural assets for posterity. This "green" commitment fits with the ancient Rwandan values of harmony with nature.

Contemporary Challenges

Due to the fast urban renewal around the city center, there are challenges for maintaining the cultural identity in architectural design.

Economic Pressures: A 2023 survey of 50 Kigali developers revealed 68% prioritize cost over cultural design due to cheaper imported materials, for example, Chinese concrete (author survey, 2023). This risks homogenizing urban aesthetics. Although there is less sustainability, the use of imported materials is favored because of their assumed robustness and usability.

Policy Gaps: At present, there are no clear mandates in urban planning patterns due to the incorporation of cultural elements. Policy interviews showed a clear demand for more specific criteria and incentives in favor of traditional designs.

[10]World Tourism Day: Rebuilding peace through women-led tourism in Rwanda - WiT. Available at: https://surl.li/fynxfd (accessed on December 03, 2024).

Loss of Craftsmanship: Traditional ways, i.e., weaving bamboo for building or making imigongo, are disappearing. This loss also restricts the number of highly skilled artisans available who can contribute to the design of a culturally appropriate nature.

Community Displacement: Urban development projects can, at times, uproot and sever communities from culturally major areas and traditional building practices.

Innovative Practices and Opportunities

Rwanda's urban centers, particularly Kigali, are experiencing a renaissance in architectural design, characterized by innovative practices that address contemporary challenges while honoring cultural heritage. With the country's continued rapid development, architects and urban planners are searching for new ways of thinking and using methods and technologies not only to improve the usability of urban areas but also to foster sustainability and civic engagement.

Innovative Practices

Sustainable Building Materials: Rwanda's Green Building Organization has reported a significant increase in the use of clay or earth brick, which reduces emissions by 60% compared to concrete[11], and by 2030 is expected to reduce carbon emissions by 38%[12,13] (Fig.6), showing Rwanda's Nationally Determined Contributions.

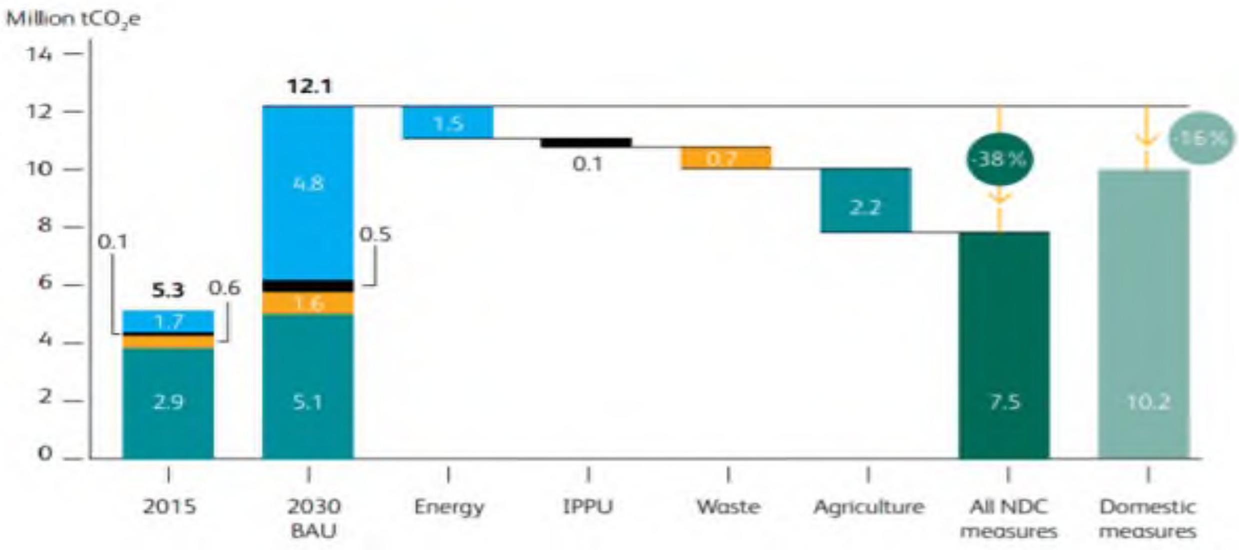

Fig. 6. *Rwanda's Nationally Determined Contributions*[14,15]

Local materials (e.g., clay, bamboo, and recycled materials) are being used increasingly in construction (e.g., clay bricks from local soils that are thermally efficient and environmentally benign) and are popular building materials[16] [9]. Not only does it reduce carbon footprints, but it also helps local economies by utilizing local resources. Architects such as Jean-Paul Mugenzi have established works that demonstrate these materials and have highlighted a move back towards working more traditionally, whilst meeting contemporary requirements.

[11] GGGI. Building Green in Rwanda – The journey so far — Global Green Growth Institute. Available at: https://surli.cc/tsxrpc (accessed on December 26, 2023).

[12] Taarifa Rwanda, Rwanda vows to reduce greenhouse gas emissions in 38% by 2030. Further Africa, 2020. Available at: https://surl.li/ohlazd (accessed on August 20, 2025).

[13] Rwanda_Updated_NDC_May_2020.pdf.

[14] Taarifa Rwanda, Rwanda vows to reduce greenhouse gas emissions in 38% by 2030. Further Africa, 2020. Available at: https://surl.li/ohlazd (accessed on August 20, 2025).

[15] Rwanda_Updated_NDC_May_2020.pdf.

[16] GGGI. Building Green in Rwanda – The journey so far — Global Green Growth Institute. Available at: https://surli.cc/tsxrpc (accessed on December 26, 2023).

Green Architecture: Green architecture is being increasingly addressed in Rwanda, with an emphasis on low environmental impact designs. Engineers are incorporating green roofs, rainwater harvesting systems, and solar cells into the design works to achieve energy saving and sustainability. Below are some examples of green architecture model building, including energy-efficient infrastructure and green materials, according to the commitment of Rwanda to sustainable development[17] [2].

Kigali Convention Centre (KCC): This famous building is inspired by the ancient Rwandan king's hut. Its dome-like form and the presence of local patterns in interior units are suggestive of the way culture can be accommodated in contemporary architecture. Figure 7 shows an example of a modern building designed with a traditional shape.

Vision City*:* The planned housing scheme of Rwanda is the largest to attempt modern living within the context of cultural aesthetics. However, interviews revealed mixed reactions, with some residents finding the designs too detached from traditional values.

Community Housing in Huye*:* As part of a community-based initiative in Huye, earth bricks and thatch are combined with contemporary methods to produce low-cost, resilient housing. The present endeavors draw attention to the importance of community involvement in the protection of cultural items.

Fig. 7. *Kigali Convention Centre, a building that is designed with a traditional shape [2]*

Rwanda Green Building Organization*:* Inspires sustainable actions such as the use of bamboo and earthen materials, which are consistent with traditional construction practices.

Community-Centric Design: Community engagement is emerging as a new core of the practice of architecture in Rwanda. Architects are becoming more involved in the community in the design phase in order to guarantee a new development that meets their needs and cultural values. This participatory method creates a feeling of resident belonging and increased social unity. As exemplified by the projects of the Nyamirambo Women's Centre, the more obvious aspect of this being is that they were all created through protracted community engagement, and this has produced places that have both functional and cultural qualities.

Use of Technology: The incorporation of technology into the architectural design is revolutionizing the perception of and construction of buildings in Rwanda. Advancements like Building Information Modeling (BIM) enable architects to develop highly detailed digital models of buildings prior to starting construction work, which leads to more efficient planning and utilization of resources. Additionally, the use of drone technology for site surveys and mapping has streamlined the design process, providing accurate data for urban planning initiatives.

Adaptive Reuse: With the growth and development of urban areas, adaptive reuse has developed into an effective means for historic building preservation and contemporary use. This practice involves repurposing existing structures for new functions, thereby preserving cultural heritage while minimizing waste. In Kigali, a number of those colonial-period structures have undergone renovation into contemporary office spaces or cultural centers and can thus combine historical relevance with contemporary utility.

Opportunities

Economic Growth through Tourism: Rwanda's ambitions to be a regional tourism center provide the best prospects for adventurous architectural initiatives that engage tourists and celebrate local culture. Architectural

[17] Rwanda: How Green Building is Cost-Effective, Guarantees Long-Term Savings. Available at: https://surli.cc/yfkwhk (accessed on December 04, 2024).

designs in keeping with the Rwandan heritage can improve the quality of the tourism experience by making it conscious and highlighting the originality of Rwandan identity. Projects, such as eco-lodges, which integrate native design, can exploit this trend and contribute to sustainability.

Educational Initiatives: Rwanda educational institutions are of extreme importance in the production of future architects sensitive to local realities. When sustainability and community engagement are included in architectural coursework, academic institutions can help create a new generation of designers who are ready to address today's challenges. Partnerships between universities and local authorities can result in creative initiatives that serve both an educational function and an urban demand.

Policy Support for Sustainable Development: The Rwandan authorities have shown a commitment to sustainable development in different policies, such as green building practices and urban planning. Continuing support of these policies is a way to build a favorable space for new architectural practices to emerge. Incentives for the use of sustainable materials and systems can eventually lead architects to adopt an eco-conscious approach.

International Collaboration: The architectural streetscape in Rwanda could be enhanced through the establishment of international partnerships that export expertise and infrastructure to Rwanda. Collaborations amongst foreign architects and organizations have the potential to bring new concepts and technologies to the table and to promote the transfer of knowledge. Such collaborations have the potential to leverage local strengths and drive creative, contextually appropriate solutions for Rwanda. Here, pioneering work in architectural design is transforming the Rwandan urban fabric and offers rich opportunities for sustainable development and cultural expression. Through the use of locally sourced materials, community involvement, and technology, as well as protection of heritage through adaptive reuse, architects can help to achieve vibrant urban landscapes that express Rwandan identity and ambition for the future.

Community Perspectives

Community views have an important influence on the design of architecture in Rwanda's urban areas. As the country continues to experience rapid urbanization, understanding the needs, values, and aspirations of local communities is essential for creating spaces that are functional, culturally relevant, and inclusive. The involvement of the community in the shaping of architectural practices in Rwanda is described with emphasis on the role of participatory design and the influence of local voices in the process of urban development.

Importance of Community Engagement

Reflecting Local Needs and Aspirations: Community engagement guarantees that the design of buildings is in accordance with their particular demands and desires for living in them. When architects take part in planning and design processes with local populations, architects can effectively consider and incorporate insights on the best use of space by its target users. This methodology promotes a feeling of belonging within the community, as input is reflected in the end designs. For instance, the work of the Nyamirambo Women's Center has been able to incorporate local women into the design process, hence achieving an intervention that not only responds to their needs but also acts as a cultural center for the community. Participatory design projects like this can give residents a voice in designing their environment.

Enhancing Social Cohesion: Design projects that embed community perspectives can promote social integration between members of a community in a neighborhood. Designs that are influenced by user input from members of the local population can promote community interaction and cooperation. For example, public parks and community centers representing ethnic cultures of the local indigenous population can evolve into social gathering points, fostering communal cohesion. In Rwanda, where communal ethos is deeply embedded, developing those areas in which social interaction can be fostered remains critical in building robust communities. Architects who consider these components help to create a feeling of belonging and oneness amongst residents.

Challenges to Community Engagement

Limited Awareness and Education: A factor that can hamper good community involvement in architectural design is poor understanding and knowledge of the design process on the part of the residents. Many community members may not be familiar with architectural concepts or may lack confidence in expressing their ideas. This can lead to underrepresentation of certain voices, particularly marginalized groups. To overcome this challenge, architects and urban designers should spend time educating communities on how they design and encourage the involvement of all social groups. Forums, focus groups, and public meetings can offer residents spaces to articulate their views and participate in conversations on urban development.

Balancing Diverse Perspectives: Communities are by no means homogeneous, and diverse needs and priorities exist amongst minority groups. Achieving congruence of these varied viewpoints is also a challenging task for architects in order to design for inclusiveness. Competing interests may occur when land use, resource distribution, or cultural representation are considered. To navigate these complexities, architects should adopt a collaborative approach that seeks consensus among community members. Encouraging open discussion and compromise can help ensure that a diverse range of voices are heard and taken into account during the design process.

Successful Examples of Community-Centric Design

The Kigali Genocide Memorial: The Kigali Genocide Memorial is a powerful case study of how the community perspective can influence architectural design to express shared memory and mending. The memorial was designed in close collaboration with survivors and community leaders, not only to remember the victims but also to provide a place for further reflection and learning. The design draws upon aspects of Rwandan culture to foster a place of remembrance and reconciliation.

Urban Green Spaces: The urban greening projects in the city of Kigali have also shown the importance of community involvement. Parks and recreation area development projects have included local community participation in the selection of preferred locations and features. Through involving the community, these green spaces not only contribute to environmental sustainability but also function as important social spaces for entertainment and interaction.

Comparative lessons from other African nations

In Rwanda, the architectural scene is changing fast, under the influence of localism along with internationalism. Since the country aims to urbanize its cities in its drive to preserve its cultural identity, it seems useful to look at similar experiences in other African countries. The urbanization rate of Rwanda is forecast to increase from 18.4% to 35% by 2024 using strong political commitment and large investments in infrastructure [10]. As growth poles, the government has listed 6 secondary cities and given primary importance to urban planning concepts that are both climate-sensitive and create public open spaces. These efforts are consistent with wider trends in African urbanism around sustainability and participation.

Sustainability in Design: There is growing adoption of sustainable architectural practices across much of the African continent, all of which adapt to local climates and resource use conditions. On the one hand, traditional building practices in Burkina Faso use local materials and passive cooling solutions, and these are translatable to Rwanda's context. Integration of green space and eco-friendly materials is also stressed in South African urban planning, with cities such as Cape Town adopting green building codes to improve urban resilience [11-13].

Cultural Relevance and Identity: Architectural designs, which represent ethnic and historical affiliations of a given region, play an important role in creating an individual sense of identity. In Ethiopia, for example, the incorporation of traditional patterns and materials into contemporary design has been an effective way to preserve indigenous culture and adhere to modernity [14,15]. Rwanda can benefit from similar approaches by incorporating local architectural styles and community input into urban development projects, ensuring that new constructions resonate with the local populace.

Community Engagement and Participatory Design: Successful projects for urban areas in Kenya and Tanzania have shown the need to engage in the planning of projects by members of the communities. Initiatives that prioritize public participation lead to designs that better meet the needs of residents and enhance social cohesion [16,17]. It may be possible to include in Rwanda's continuing work to update master plans for its secondary cities sessions with participatory workshops that solicit input into local community needs and desires as a way of ensuring that developments are suitable to their needs and aspirations. Table 1 shows a comparative analysis of architectural design in Rwanda's urban centers with other countries in Africa.

Table 1. Comparative analysis of Urban Centers

Country	Architectural strategy	Key features	Potential application in Rwanda
Burkina Faso	Sustainable local materials	Use of earth and clay for thermal comfort	Promote local materials in construction projects
Ethiopia	Cultural integration	Traditional motifs in modern architecture	Incorporate Rwandan cultural elements in designs
Kenya	Community participation	Engaging locals in planning and design processes	Implement participatory planning workshops
South Africa	Green building standards	Eco-friendly materials and energy-efficient designs	Develop green building regulations for urban areas
Tanzania	Mixed-use developments	Combining residential, commercial and public spaces	Encourage mixed-use developments in urban planning
Ghana	Adaptive reuse strategies	Transformation of colonial-era structures into modern or cultural centers	Adopt similar strategies to preserve its architectural and cultural heritage

Adaptive Reuse of Historical Buildings and Policy Frameworks Supporting Sustainable Development: Ghana has effectively utilized adaptive reuse strategies to preserve historical buildings while meeting contemporary needs. This approach not only conserves cultural heritage but also revitalizes urban spaces. Ghana's government has implemented policies supporting sustainable urban development, including incentives for green building practices and community engagement in planning processes. For example, the transformation of colonial-era structures into modern offices or cultural centers in Accra demonstrates how adaptive reuse can enhance urban identity. These frameworks have facilitated the integration of sustainability into architectural design. Rwanda can adopt similar strategies to preserve its architectural heritage while accommodating modern functionality and learn from Ghana's experience by strengthening its policy frameworks to encourage sustainable practices among architects and developers[18] [18].

Learning from other African countries on the design and implementation of innovative solutions presents both opportunities and challenges and provides experiences that can help shape architectural design in Rwanda's cities. Through the combination of the approaches of informal settlements, the fundamental principle of public health in planning, community-based approaches, eco-friendly practices, adaptive reuse, and policy reform, Rwanda can face its particular challenges and develop a rich architectural appearance.

Summary of Findings

A summary of the key challenges identified and the culturally sustainable solutions they necessitate is presented in Table 2.

[18] Urban Planning in Sub-Saharan Africa, Colonial and Post-Colonial Planning Cultures. 2015.

Table 2. Challenges and Proposed Solutions for Culturally Sustainable Architecture in Rwanda

Challenge	Solution	Example	Impact
Imported concrete dominance	Local clay bricks incentives	Kigali Green Village	60% lower CO2 emissions
Displaced communities	Participatory design workshop	Nyamirambo Women's Center	85% resident satisfaction

Despite promising practices in Rwanda, the broad implementation of culturally integrated approaches requires the restructuring of policy, education, and community involvement systems. Three key findings emerge:

1. Cultural-environmental synergy: The projects using local materials, for instance, clay bricks, like at Kigali Green Village, saw 60% lower emissions and 30% cost savings[19] .
2. Community-driven success: Participatory designs like Nyamirambo Women's Center reported 85% residents' satisfaction vs 12% for top-down projects (author interviews, 2023).
3. Policy gaps: The interviews with planners in Kigali in 2023 revealed that construction projects that complied with cultural design guidelines remained low (author interviews, 2023).

Suggestions and Conclusion

Suggestions

According to the following recommendations, efforts should be made to safeguard and highlight cultural influences in urban architectural designs in Rwanda:

Policy Reform: In terms of tax incentives, the Rwanda government must reduce taxes for all new projects that use more than 50% local materials (e.g., clay, bamboo). The Rwanda government must mandate imigongo patterns or circular motifs in facades for all public buildings per Kigali Master Plan[20]. Monitoring establishes a cultural architecture task force to audit compliance annually.

Capacity Building: Provide training programs aimed at young artisans to master traditional craftsmanship, including weaving, carving, and imigongo design. This will guarantee the survival of original skills and open up work opportunities at the same time. Architectural and design institutions in Rwanda should include courses on vernacular design and sustainable building techniques in their respective programs.

Community Engagement: Urban development schemes should include residents in the design process. Participatory planning guarantees adherence to community values as well as meeting community needs. Development and planning should organize workshops and surveys to obtain feedback from residents on on culturally sensitive design preferences.

Public Awareness and Advocacy: Launch national campaigns to emphasize the role of cultural heritage in architecture. This will build pride in traditional styles and create a demand for culturally embedded solutions. Internationalization: work with internationally minded and culturally appropriate design organizations and firms that have a proven history of sustainable design practice. Exchange programs can foster new ideas as well as reinforce local consciousness.

Conclusion

Rwandan urban architecture stands at a crossroads: globalized homogeneity or culturally rooted innovation. Evidence shows that integrating traditional, for example, inzu-inspired circular designs with sustainable materials like clay bricks can reduce emissions by 60% while fostering identity[21]. To achieve this, Rwanda

[19] GGGI. Building Green in Rwanda – The journey so far — Global Green Growth Institute. Available at: https://surli.cc/tsxrpc (accessed on December 26, 2023).
[20] P. Rubingisa, Kigali Master Plan (Report). Available at: https://surl.lt/gybppr (accessed on October 24, 2023).
[21] GGGI. Building Green in Rwanda – The journey so far — Global Green Growth Institute.

must scale participatory models like the Nyamirambo Women's Center, enforce green cultural policies with penalties for non-compliance, and invest in artisan training to revive crafts like imigongo weaving. This blueprint could position Rwanda as a leader in African neo-vernacular architecture.

This paper has shown that the accelerating urbanism occurring in cities such as Kigali and Huye holds both threats and rewards. Although globalization tends to push towards standardized design, Rwanda has the opportunity to develop a distinctive architectural identity as a tribute to its rich cultural heritage. Through the implementation of sustainable and locally adapted mechanisms, Rwanda is potentially able to serve as an example for the other countries in Africa undergoing a similar transformation. The achievement of this task depends upon the work of policymakers, architects, craftspersons, and citizens. By planned action, it will still be possible to achieve a cohesive mix of modernity and tradition in Rwanda so that its urban spaces do not ironically miss out their national character.

Conflict of Interest

The author declares no conflicts of interest.

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References

[1]. I. Gubic, O. Baloi, Public Open Space Initiatives for Healthier Cities in Rwanda. The Journal of Public Space, 5 (2), 129-146, 2020. Doi: https://doi.org/10.32891/jps.v5i2.1287

[2]. I. Gubić, S. Leontiadis, J. Bugirimfura, A. Karigirwa, J. Mugema, A. Yuhi, Traditional Circular Plan Housing for Rapidly Urbanizing Rwanda. Facta universitatis - series: Architecture and Civil Engineering, 20 (3), 261-275, 2022. Doi: https://doi.org/10.2298/FUACE221101020G

[3]. T. Kabera, D.C. Wilson, H. Nishimwe, Benchmarking Performance of Solid Waste Management and Recycling Systems in East Africa: Comparing Kigali Rwanda with other Major Cities. Waste Management & Research, 37 (1), 58-72, 2019. Doi: https://doi.org/10.1177/0734242X18819752

[4]. A. Purdeková, D. Mwambari, Post-Genocide Identity Politics and Colonial Durabilities in Rwanda. Critical African Studies, 14 (1), 19-37, 2021. Doi: https://doi.org/10.1080/21681392.2021.1938404

[5]. B.M. Michieletto, Building the Future Urban Structure: Kigali's Green City Project. Athens Journal of Architecture, 11, 1-17, 2025.

[6]. M. Michieletto, O. Adedayo, V.B. Mukanya, African Housing Renaissance: The Case of Gacuriro Valley Satellite Settlements, Kigali, Rwanda. Urban Planning, 4 (3), 265-290, 2019. Doi: https://doi.org/10.17645/up.v4i3.2210

[7]. L. Mbereyaho, J. Malonza, Architecture, Building Design and Construction in Rwanda. Proceedings of the Conference: Oscar Von Muller Forum, Germany, Munich, April 15, 2010.

[8]. J. Niyoyita, L.Haiying, Study on Rwandan Traditional Architecture. Proceedings of the International Conference on Architecture: Heritage, Traditions and Innovations, 2019. Doi: https://doi.org/10.2991/ahti-19.2019.36

[9]. F. Mwizerwa, D. Buddhi, Status of Green Buildings in RWANDA: Need and Scope 8 (7), 199-208, 2019. Available at: https://surl.li/daxgst (accessed on July 27, 2019).

[10]. J.M. Malonza, A.A. Ortega, Fissures in localizing Urban Sustainability: The Case of Rwanda. GeoJournal, 87 (1), 147-166, 2022. Doi: https://doi.org/10.1007/s10708-020-10239-8

[11]. L. Andres, P. Jones, S.P. Denoon-Stevens, L.M. Silva Marques, Negotiating Polyvocal Strategies: Re-Reading de Certeau through the Lens of Urban Planning in South Africa. Urban Studies, 57 (12), 2440-2455, 2019. Doi: https://doi.org/10.1177/0042098019875423

[12]. L. Melgaço, L.X. Pinto Coelho, Race and Space in the Postcolony: A Relational Study on Urban Planning Under Racial Capitalism in Brazil and South Africa. City & Community, 21 (3), 214-237, 2022. Doi: https://doi.org/10.1177/15356841221087195

Available at: https://surli.cc/tsxrpc (accessed on December 26, 2023).

[13]. M. Jagarnath, T. Thambiran, M. Gebreslasie, Heat Stress Risk and Vulnerability under Climate Change in Durban Metropolitan, South Africa—Identifying Urban Planning Priorities for Adaptation. Climatic Change, 163 (2), 807-829, 2020. Doi: https://doi.org/10.1007/s10584-020-02908-x

[14]. S. Awgichew, E. Ademe, History Education for Nation-Building in Ethiopia, Germany, Rwanda, South Africa, Switzerland, and USA: A Comparative Analysis. Cogent Education, 9 (1), 2022. Doi: https://doi.org/10.1080/2331186X.2022.2113210

[15]. A. Kebede, D. Amsalu, D. Yosef, Looking Back Thinking Ahead Towards the Vernacular Architecture of Gurage, Ethiopia. Discover Sustainability, 5 (1), 2024. Doi: https://doi.org/10.1007/s43621-024-00206-5

[16]. A. Kemajou, A.A. Konou, R. Jaligot, J. Chenal, Analyzing Four Decades of Literature on Urban Planning Studies in Africa (1980–2020). African Geographical Review, 40 (4), 425-443, 2020. Doi: https://doi.org/10.1080/19376812.2020.1844025

[17]. P.B. Cobbinah, M. Addaney, The Geography of Climate Change Adaptation in Urban Africa. Palgrave Macmillan, 2019. Doi: https://doi.org/10.1007/978-3-030-04873-0

[18]. W.L. Filho, D. Jacob, H.A. Shishaye, Handbook of Climate Services. Climate Change Management, 2020. Doi: https://doi.org/10.1007/978-3-030-36875-3

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APPLICATION OF BASALT FIBERS AND CEMENT THROUGH FDR TECHNOLOGY IN THE KM 93+880 SECTION OF THE M2 YEREVAN–GORIS–MEGHRI HIGHWAY

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Abstract: *The maintenance and rehabilitation of road networks remain among the most critical challenges in the global road construction sector, as increasing traffic volumes and pavement deterioration demand efficient solutions. Road repair and maintenance are essential not only for ensuring traffic safety but also for optimizing economic expenditures. Full-Depth Reclamation (FDR) is a pavement rehabilitation method in which the existing pavement—comprising the asphalt concrete surface, the base layer, and in some cases, additional base and subbase layers—is uniformly pulverized and blended to a predetermined depth, producing an improved, homogeneous base material. FDR is carried out entirely on-site without the application of heat. The treatment depth depends on the structure of the existing pavement and typically ranges from 100 to 300 mm. Compared to other technologies for rehabilitating flexible pavements, FDR significantly reduces the need for importing new materials, lowers energy consumption, and decreases harmful atmospheric emissions. The implementation of FDR in road construction began several decades ago, initially involving various mechanisms for pavement treatment, including pulverizers, scarifiers, mixers, and a range of additives. However, the adoption of high-powered self-propelled reclaimers provided significant momentum to the use of FDR, enabling deeper processing, higher productivity, and more reliable control of the stabilization process when additives are introduced. This article examines the impact of applying Full-Depth Reclamation (FDR) technology with cement and basalt fibers as additives on the strength and crack resistance of road pavements. The km 93+880 section of the M2 Yerevan–Goris–Meghri highway in the Republic of Armenia was selected as the experimental test site.*

Keywords: *Basalt fibers, cement, additives, Full-Depth Reclamation (FDR) technology, asphalt concrete.*

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Introduction

The growing population, advancing economies, and increasing transport volumes have created significant challenges for the global road construction sector—challenges that underscore the urgent need to maintain and rehabilitate road networks. Over the past decades, a vast network of asphalt concrete roads has been developed; however, many of these roads are now nearing or have already exceeded their service life due to heavy loads, climatic conditions, and degradation. Implementing restoration works on time can substantially prolong road lifespan while minimizing financial costs [1]. Full Depth Reclamation (FDR) is one of the most effective methods for restoring asphalt concrete pavements, widely used for its resource efficiency and environmental benefits. This technology makes it possible to recycle existing road layers, thereby reducing the need for new materials, energy consumption, and emissions. FDR eliminates problems such as rutting and cracking, and it enhances the structural strength of the road through the use of stabilizing additives, including Portland cement, bituminous emulsion, or foamed bitumen [2-6]. In both developed and developing countries, the road network plays a vital role in economic and social development, and the application of FDR can offer a cost-effective and environmentally sustainable solution. Furthermore, the use of innovative materials—such as basalt fiber—is critically important for enhancing the quality of asphalt concrete mixtures. Basalt fiber is characterized by high mechanical strength, thermal stability, and resistance to cracking, all of which contribute to the greater durability of the road. Its use also reduces bitumen penetration and improves the properties of the mixture, which is particularly important in environments characterized by temperature fluctuations and heavy loads [7-10]. Given the climatic and geological conditions of Armenia, the integrated application of basalt fiber and FDR technology can considerably enhance pavement performance while reducing maintenance costs and environmental impact.

Materials and Methods

Properties and Manufacturing of Basalt Fibers

FDR technology is a pavement restoration method in which the existing surface—typically the full depth of the asphalt concrete layer, along with the base and, in some cases, additional subbase and subgrade layers to a specified depth—is thoroughly pulverized and mixed to produce a homogeneous, improved base material. FDR is performed entirely on-site without the use of thermal processing. The processing depth depends on the existing road structure and generally ranges from 100 to 300 mm. Compared to other flexible pavement restoration methods, the use of FDR significantly reduces the need for new materials, lowers energy consumption, and minimizes the emission of harmful substances into the atmosphere. From a structural standpoint, FDR technology used in the restoration of flexible pavements effectively addresses all issues related to rutting and reflective cracking on the road surface [11]. Various additives—such as basalt fibers, cement, and others—may be used during the implementation of FDR technology to enhance the strength and crack resistance of the reclaimed material. In recent decades, basalt fibers have been considered a strengthening agent for composite materials. Basalt is a volcanic rock widely distributed across the world. Basalt fibers are produced by melting natural basalt at temperatures ranging 1300–1700°C, followed by fiber formation through high-speed rotating rollers. The chemical composition of basalt includes SiO_2 (45–55%), Al_2O_3 (15–20%), Fe_2O_3 (5–15%), CaO (5–10%), and other oxides, all of which contribute to its high durability [12-14]. Tensile strength: Basalt fibers exhibit tensile strengths ranging from 3000 to 4000 MPa, which is 20–30% higher than that of glass fibers (2500–3000 MPa) and steel (3500–4500 MPa). Modulus of elasticity: Their elastic modulus ranges from 85–100 GPa providing sufficient rigidity to resist deformation under heavy loads. Density: With a density of 2.6–2.8 g/cm^3— three times lighter than steel (7.8 g/cm^3)— basalt fibers are advantageos in handling and application due to their lightweight nature. Heat resistance: Basalt fibers can withstand temperatures up to 700°C without undergoing structural degradation, unlike synthetic fibers, which typically melt at 200–300°C. Corrosion Resistance**:** Basalt is chemically stable in both alkaline (pH 12–14) and acidic (pH 2–4) environments, in contrast to steel, which is vulnerable to rust [15-18]. Extensive research conducted by numerous scientists and experts has clearly demonstrated that the use of basalt fibers significantly enhances the crack resistance and overall strength of asphalt concrete mixtures. Their experimental findings indicate that a fiber content of 0.4% is considered the most effective and optimal amount for asphalt concrete mixtures, ensuring maximum performance and stability [19-21]. Cement (primarily Portland cement) is used in FDR as a binding agent, enhancing the stiffness and load-bearing capacity of the mixture. The chemical composition of cement includes CaO (60–65%), SiO_2 (20–25%), Al_2O_3 (5–7%), and Fe_2O_3 (2–4%). It exhibits a compressive strength of 5–10 MPa, stiffness of 10–15 GPa, and moisture resistance of 80–90% [22].

Results and Discussion

Preliminary assessment and Planning

The Full-Depth Reclamation (FDR) process begins with a comprehensive assessment of the existing pavement condition. At this stage, the extent of surface deterioration, the structure of the base layer, and the properties of the constituent materials are carefully examined. The purpose of this assessment is to determine the appropriate reclamation depth and to select the types of binding agents required for the process (Fig.1).

Fig. 1. *Section of road under reclamation*

For this purpose, samples taken from the designated road section are sent for laboratory testing. The analyses make it possible to determine the type and quantity of binding agents, as well as the particle size distribution (gradation) of the road materials. This stage is particularly important in the mountainous areas of Armenia, where roads are exposed to harsh climatic conditions and heavy mechanical loads. Figure 2 illustrates the determination of the particle size distribution of the road pavement under laboratory conditions.

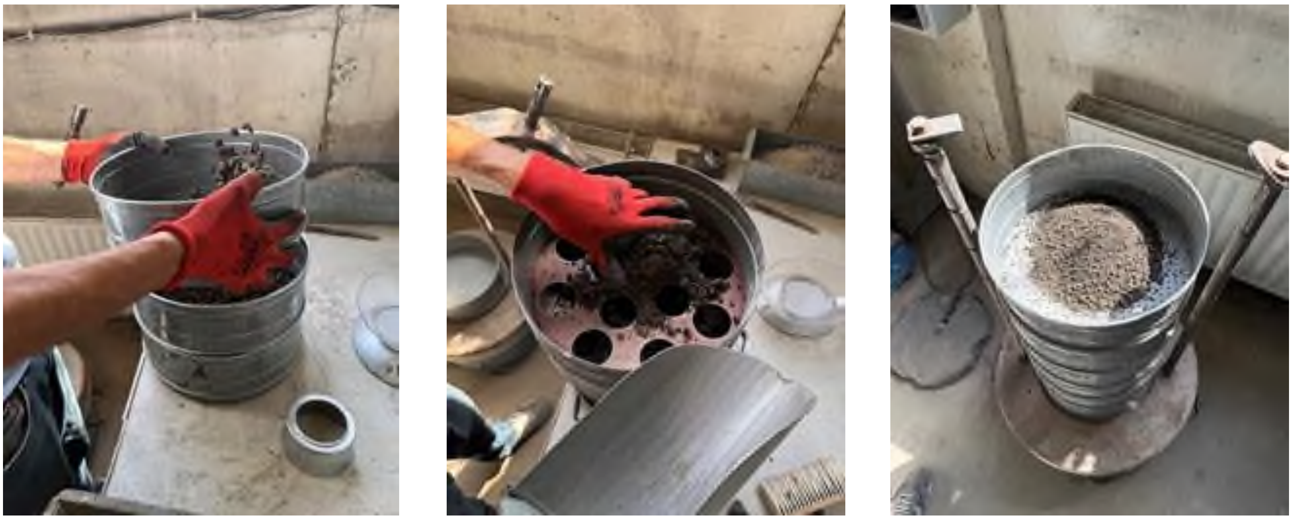

Fig. 2. *Determination of the particle size distribution of milled asphalt concrete*

Based on the analysis of the grain-size composition of the road pavement, four separate experimental sections were selected to evaluate the effectiveness of different binding materials and their combinations. The additives used in the experiments were sourced from “ARMBASALT” CJSC, which supplied basalt fibers, and from “ARARATCEMENT” CJSC, which provided the cement. A different approach is applied in each test section (Figs. 3,4):

1. Section 1: FDR is performed without adding any binding agents to assess the reclaimed material’s natural strength and stability in the absence of additives.
2. Section 2: Basalt fibers measuring 20 mm in length are added at a content of 0.4%.

Fig. 3. *First and second test sections*

3. Section 3: 4% cement is used as the binding agent.
4. Section 4: basalt fibers (20 mm in length, 0.4% content) are combined with 4% cement as binding agents.

Fig. 4. *Third and fourth test sections*

Execution of FDR

The FDR process begins with the pulverization of the existing pavement and base layer to a depth of 25 cm. This depth is determined by considering the condition of the existing pavement. Pulverization is carried out using specialized equipment such as reclaimers, which process the asphalt concrete layer and base material into a uniform granular mixture. This process enables the reuse of existing road materials, reducing the need for new materials and promoting environmental sustainability. After pulverization, the selected binding agents are added to each test section in accordance with the plan outlined above. The binding agents are mixed with the pulverized material using on-site mixing equipment. This process ensures the uniform distribution of materials, which is essential for achieving a homogeneous and stable base. After mixing, the mixture is compacted using a roller to reduce air voids and enhance the structural strength. Compaction is performed in multiple stages to achieve a smooth and stable surface. Subsequently, profiling is carried out to shape the road surface with the required gradient and smoothness (Fig.5).

Fig. 5. *Full-Depth reclamation and profiling of road pavement*

Quality Control

After the addition of binding agents and compaction, the road base is left to undergo the curing phase. In the case of cement, the curing process may last between 3 and 7 days, depending on humidity and weather conditions. In the case of basalt fibers, the curing time may be shorter; however, when combined binding agents are used (e.g., cement and basalt fibers), the curing duration depends on the cement hardening process. During the curing period, it is necessary to maintain a moist environment to ensure proper cement hardening. Core samples are extracted from each test section one week after completion of the works, for laboratory analysis. However, as shown in Figure 6, core samples could only be taken from the section where cement alone was used—with core lengths ranging from 10 to 12 cm—and from the section where both cement and basalt fibers were used—with core lengths ranging from 22 to 24 cm. No binding occurred in the other sections.

Fig. 6. *Core sample extraction*

The extracted core samples are tested under laboratory conditions to evaluate their strength and crack resistance, providing insight into which combination of binding agents yields the most effective results. Test results are evaluated against established standards to verify that the reclaimed road meets the technical requirements. Upon completion of the curing period, the samples underwent thorough compression testing to precisely assess their compressive resistance and strength properties. Before compression testing, each sample—maintained under strictly controlled conditions—is weighed for data recording. Subsequently, the samples were placed into the compression testing device, as illustrated in Figure 7.

Fig. 7. *Compressive strength test of core samples*

The following indicators were obtained from the test, as presented in the Table.

Table. Compressive Strength Results of Cement and Cement–Basalt Fiber Specimens

№	Description	Mass (g)	Maximum compressive strength (MPa)
1.	Sample 1 from cement section	1322	3.2
2.	Sample 2 from cement section	1337	3.3
3.	Sample 3 from cement section	1334	3.2
4.	Sample 1 from cement and basalt fiber section	1352	3.75
5.	Sample 2 from cement and basalt fiber section	1412	3.7
6.	Sample 3 from cement and basalt fiber section	1345	3.79

The average compressive strength of samples from the cement section is 3.2 MPa, while the average compressive strength of samples from the cement and basalt fiber section is 3.75 MPa. Technical specifications and experimental methods were carried out in accordance with the standards in force in the Republic of Armenia, namely GOST 9128-2013, GOST 12801-98, RABC 32-01-2022, and SP 78.13330.2012

Economic analysis

The calculations are based on official data from the Republic of Armenia.

- FDR with cement as an additive
  - Implementation cost of FDR technology per 1 m²: 2,670 AMD
  - Cost of adding 4% cement (16 kg) per 1 m²: 960 AMD
  - Total cost per 1 m²: 3,630 AMD
  - Service life: 20 years

- **FDR with cement and basalt fibers as additives**
  - Implementation cost of FDR technology per 1 m²: 2,670 AMD
  - Cost of adding 4% cement (16 kg) per 1 m²: 960 AMD
  - Cost of adding 0.4% basalt fibers (1.6 kg) per 1 m²: 500 AMD
  - Total cost per 1 m²: 4,130 AMD
  - Service life: 24 years

Conclusion

Full-Depth Reclamation (FDR) is an effective technology for road rehabilitation. For this study, the section at Km 93+880 of the M2 Yerevan–Goris–Meghri road was examined. Test results indicate that the combination of basalt fibers (0.4% by content, 20 mm in length) and 4% cement significantly improves the physico-mechanical properties of asphalt concrete mixtures, including compressive strength and crack resistance. This proportion yields more optimal results compared to using only 4% cement. The tests conducted on the km 93+880 section of the M2 Yerevan–Goris–Meghri road confirm that the road pavement produced with such mixtures outperforms traditional asphalt concrete in terms of performance indicators. The obtained results indicate that the service life of the road increases by 17–18%, while the cost rises by 13–14%, which is justified from a financial perspective. These results are of significant importance for the road construction sector of the Republic of Armenia, where the quality and long-term durability of road infrastructure play a vital role in the country's economic advancement and social development. The test results indicate that the use of basalt fibers and cement through FDR technology has a significant positive effect on asphalt concrete pavement. It enables the construction of roads with enhanced capacity to withstand heavy loads and to ensure long-term stability.

Conflict of Interest

The author declares no conflicts of interest.

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References

[1]. H.H. Gyulzadyan, A.S. Ghazaryan, Analysis of International Practice in the Application of Asphalt Concrete Recycling Technology. Scientific Papers of the National University of Architecture and Construction of Armenia, 3 (66), 2017, 32-39.

[2]. A. Behnood, M.M. Gharehveran, F.G. Asl, M. Ameri, Effects of Copper Slag and Recycled Concrete Aggregate on the Properties of CIR Mixes with Bitumen Emulsion, Rice Husk Ash, Portland Cement and Fly Ash. Construction and Building Materials, 96, 2015, 172-180. Doi: https://doi.org/10.1016/j.conbuildmat.2015.08.021

[3]. H.H. Gyulzadyan, Kh.S. Chkolyan, Analysis of Road Pavements' Full Depth Reclamation Experience. Scientific Papers of the National University of Architecture and Construction of Armenia, 1 (82), 2022, 31-40.

[4]. M. Bocci, A. Grilli, F. Cardone, A. Graziani, A Study on the Mechanical Behaviour of Cement–Bitumen Treated Materials. Construction and Building Materials, 25 (2), 2011. 773-778. Doi: https://doi.org/10.1016/j.conbuildmat.2010.07.007

[5]. A. Graziani, C. Godenzoni, F. Cardone, M. Bocci, Effect of Curing on the Physical and Mechanical Properties of Cold-Recycled Bituminous Mixtures. Materials & Design, 95, 2016, 358-369. Doi: https://doi.org/10.1016/j.matdes.2016.01.094

[6]. B. Dolzycki, M. Jaczewski, C. Szydlowski, The Long-Term Properties of Mineral-Cement-Emulsion Mixtures. Construction and Building Materials, 156, 2017, 799-808. Doi: https://doi.org/10.1016/j.conbuildmat.2017.09.032

[7]. A. Ibrahim, S. Faisal, N. Jamil, Use of basalt in asphalt concrete mixes. Construction and Building Materials, 23 (1), 2009, 498-506. Doi: https://doi.org/10.1016/j.conbuildmat.2007.10.026

[8]. N. Morova, Investigation of Usability of Basalt Fibers in Hot Mix Asphalt Concrete. Construction and Building Materials, 47, 2013, 175-180. Doi: https://doi.org/10.1016/j.conbuildmat.2013.04.048
[9]. Y. Zheng, Y. Cai, G. Zhang, H. Fang, Fatigue Property of Basalt Fiber-Modified Asphalt Mixture under Complicated Environment. Journal of Wuhan University of Technology-Mater. Sci. Ed., 29 (5), 2014, 996-1004. Doi: https://doi.org/10.1007/s11595-014-1033-1
[10]. C. Gao, W. Wu, Using ESEM to Analyze the Microscopic Property of Basalt Fiber Reinforced Asphalt Concrete. International Journal of Pavement Research and Technology, 11(4), 2018, 374-380. Doi: https://doi.org/10.1016/j.ijprt.2017.09.010
[11]. G. Bergeron, Performance des techniques de retraitement en place et de recyclage à froid au Québec, in: Congrès annuel de 2005 de l’Association des transports du Canada à Calgary (Alberta), 2005.
[12]. T. Czigány, Trends in Fiber Reinforcements – the Future Belongs to Basalt Fiber. Express Polymer Letters, 1 (2), 2007, 59. Doi: https://doi.org/10.3144/expresspolymlett.2007.11
[13]. Q. Liu, M.T. Shaw, R.S. Parnas, A-M Mcdonnell, Investigation of Basalt Fiber Composite Mechanical Properties for Applications in Transportation. Polymer Composites, 27 (1), 2006, 41-48. Doi: https://doi.org/10.1002/pc.20162
[14]. T. Czigány, Discontinuous Basalt Fiber-Reinforced Hybrid Composites, in: K. Friedrich, S. Fakirov, Z. Zhang (eds.), Polymer Composites: From Nano to Macro-scale. Springer, Boston, MA, 2005, 309-328. Doi: https://doi.org/10.1007/0-387-26213-X_17
[15]. V. Dhand, G. Mittal, K.Y. Rhee, S.J. Park, D. Hui, A Short Review on Basalt Fiber Reinforced Polymer Composites. Composites Part B: Engineering, 73, 2015, 166-180. Doi: https://doi.org/10.1016/j.compositesb.2014.12.011
[16]. A. Dorigato, A. Pegoretti, Fatigue Resistance of Basalt Fbers-Reinforced Laminates. Journal of Composite Materials, 46 (15), 2012, 1773-1785. Doi: https://doi.org/10.1177/0021998311425620
[17]. V.V. Gur'ev, E.I. Neproshin, G.E. Mostovoi, The Effect of Basalt Fiber Production Technology on Mechanical Properties of Fiber. Glass and Ceramics, 58, 2001, 62-65. Doi: https://doi.org/10.1023/A:1010901615857
[18]. T. Deak, T. Czigany, Chemical Composition and Mechanical Properties of Basalt and Glass Fbers: A comparison. Textile Research Journal, 79 (7), 2009, 645–651. Doi: https://doi.org/10.1177/0040517508095597
[19]. Xin Yan, Ronghua Ying, Jian Jin, Yuntai Zhang. Study on Cracking Resistance of Basalt Fiber-Reinforced Microbond Asphalt Macadam. Advances in Civil Engineering, 2021, 6647766. Doi: https://doi.org/10.1155/2021/6647766
[20]. K. Singha, A Short Review on Basalt Fiber. International Journal of Textile Science, 1 (4), 2012, 19-28. Doi: https://doi.org/10.5923/j.textile.20120104.02
[21]. A. Cetin, B. Evirgen, A. Karslioglu, A. Tuncan. The Effect of Basalt Fiber on the Performance of Stone Mastic Asphalt. Periodica Polytechnica Civil Engineering, 65 (1), 2021, 299-308. Doi: https://doi.org/10.3311/PPci.14190
[22]. S.P. Dunuweera, R.M Rajapakse, Cement Types, Composition, Uses and Advantages of Nanocement, Environmental Impact on Cement Production, and Possible Solutions. Advances in Materials Science and Engineering, 2018. Doi: https://doi.org/10.1155/2018/4158682

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INFLUENCE OF THERMAL INSULATION MATERIALS ON NATURAL GAS CONSUMPTION UNDER COLD-CLIMATE CONDITIONS

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Abstract: *This article presents a comprehensive and in-depth study focused on improving the energy efficiency of residential buildings in cold-climate regions, using the town of Sisian in Armenia's Syunik Province as a case study. The primary objective of the research is to evaluate the effectiveness of thermal insulation applied to the external load-bearing structures, specifically the exterior walls and roof of a typical two-story residential house. The study emphasizes the use of polyurethane foam, a modern insulating material known for its high thermal resistance, durability, and ease of application. The research was conducted during the heating season, a period marked by high energy consumption due to cold weather, which provided an ideal context for analyzing thermal losses and energy demand. Through a detailed comparison of pre- and post-insulation energy performance, the results demonstrated a substantial reduction in heat loss through the building's envelope. The application of polyurethane foam not only minimized energy loss but also led to a significant decrease in the total energy required to maintain indoor thermal comfort. This translates into lower energy bills for residents and a reduced environmental footprint, given the lowered demand for heating fuels, such as natural gas or electricity. The findings of this study are particularly important for regions like Sisian and other mountainous or high-altitude settlements in Armenia, where harsh winters and insufficient insulation in older housing stock lead to excessive energy consumption. By highlighting the benefits of thermal insulation in terms of energy savings, comfort, and sustainability, the research advocates for broader adoption of energy-efficient construction practices. Moreover, the study offers essential insights for policymakers, architects, and engineers, reinforcing the need to revise national building codes and develop targeted energy efficiency programs. Overall, the research serves as a valuable contribution to Armenia's efforts toward sustainable development and energy independence.*
Keywords:*.heating, energy, climate, data, efficiency, thermal insulation, sustainability.*

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Introduction

In the territory of the Republic of Armenia, particularly in mountainous regions such as Syunik Province, energy consumption for residential heating constitutes a significant portion of household utility expenses. The town of Sisian, situated at an altitude of over 1,600 meters, is characterized by cold and prolonged winters, during which indoor heating is required for more than six consecutive months [1]. The existing residential building stock primarily consists of stone-structured houses built before the establishment of modern thermal insulation standards, which lack sufficient thermal performance. As a result, energy losses and low heating efficiency are widespread.

While numerous modeling studies have examined thermal insulation performance, field-validated data on seasonal energy consumption in Armenia's specific climate conditions (high-altitude cold climate, 1600m elevation, 6+ month heating seasons) remain scarce. This study provides empirical evidence of polyurethane foam insulation effectiveness through full-season measurements in actual residential conditions, offering directly applicable data for building code development and energy policy in similar cold-climate mountainous regions [2].

Thermal insulation of a building's external structures, especially walls and roofs, is considered one of the most effective methods for reducing energy losses [3]. The fuel used for heating in Sisian is natural gas (primarily methane, CH_4) supplied at 8,500 kcal/m³ (35.6 MJ/m³) calorific value, which represents the standard heating fuel for 95% of Armenian households.

Due to its low thermal conductivity, durability, affordability, and ease of application, polyurethane foam (PUF) has become widely used in the construction sector. The purpose of this study is to thermally insulate the external structures of a residential building located in Sisian using polyurethane foam, thereby improving energy efficiency.

While this study demonstrates significant energy savings through polyurethane foam insulation, we acknowledge that the experimental scope was deliberately focused on practical field measurements rather than comprehensive laboratory material characterization. The polyurethane foam properties (50 mm thickness, 35-40 kg/m³ density, 0.022 W/m·°C thermal conductivity) were verified against manufacturer specifications and ISO 8301 standards, with selection based on established performance data for cold-climate applications. Future research should include comprehensive material testing protocols such as long-term thermal stability analysis under freeze-thaw cycles, hygrothermal performance monitoring, fire resistance testing, mechanical property evaluation, and comparative studies with alternative insulation materials (mineral wool, expanded polystyrene, cellulose) to establish optimal cost-benefit relationships. Additionally, multi-building studies spanning multiple heating seasons with advanced monitoring techniques (infrared thermography, heat flux sensors) would provide robust statistical validation across different building typologies. Despite these limitations, the study's strength lies in providing empirical, field-validated data on seasonal fuel consumption reduction (2.3-fold savings) measured under authentic residential conditions across an entire heating season, offering directly applicable evidence for building code revisions and energy efficiency programs in Armenia's cold-climate mountainous regions, where practical demonstration of achievable energy savings is critically needed to support policy implementation.

Unlike studies based solely on modeling, this research is based on actual measurements, thermal balance calculations, and comparative analysis covering the entire heating season.

Materials and Methods

The study was conducted during the heating season to improve the thermal and energy balance of a typical residential building in the town of Sisian. A combined approach to data collection was applied for building analysis, which included on-site direct measurements, instrumental monitoring, long-term energy observations, and manual thermotechnical calculations [4]. The methodology comprises several key stages, which are presented below.

Material Characterization:

- Polyurethane foam: 50 mm thickness, density 35-40 kg/m³, thermal conductivity $\lambda = 0.022$ W/m·°C (verified per ISO 8301)
- Finishing system: Glass fiber reinforcing mesh embedded in mineral-based plaster (8-10 mm thickness)
- Permeability properties: Polyurethane foam – water vapor diffusion resistance factor $\mu = 30\text{-}60$; Finishing plaster – $\mu = 15\text{-}25$, allowing vapor permeability while providing weather protection

Measurement Protocol:

- Pre-insulation monitoring: October 2023 - March 2024 (full heating season)
- Post-insulation monitoring: October 2024 - March 2025 (full heating season)

Natural gas consumption measured via calibrated gas meter (±2% accuracy).

Indoor temperature maintained at 22°C ± 1°C, monitored with data loggers.

Outdoor climate data from the local meteorological station.

Quality Control:

Gas meter readings are verified weekly.

Indoor temperature consistency confirmed through continuous monitoring.

Building occupancy patterns remained constant between measurement periods.

As the subject of the study, a building characteristic of Sisian was selected, as illustrated in Figure 1. It is a two-story structure with tuff stone walls and a reinforced concrete frame. Each floor measures 9 meters in width and 10 meters in length, resulting in a total heated area of 180 m² (90 m² per floor). The building is oriented along the north-south axis, with windows predominantly facing east and west.

The main architectural and structural characteristics are as follows:

Fig. 1. *The house under consideration*

- Ceiling – 20 cm thick reinforced concrete,
- Roof – Sloped metal sheet roof separated by a 20 cm reinforced concrete slab, without thermal insulation,
- Windows – Double-glazed aluminum frames with a 12 mm air gap,
- Indoor conditions – Heated using radiators, with a regulated indoor temperature of 22°C,
- Windows and joints – All window frames were insulated with polyurethane foam and silicone to eliminate thermal bridges.

According to the architectural and floor plans (Fig.1), the building's external enclosing structures include: walls – 232.8 m², windows – 15.8 m², door – 3.6 m², ceiling – 90 m², and floor – 90 m². The external enclosing structure is of tuff type (Fig. 2), with a thermal transmittance coefficient (U-value) of 1.41 W/m²·°C. Based on the calculated outdoor air temperature, the heating and cooling loads of the building have been determined [5,6].

For residential buildings, the duration of the heating season is defined by the period during which the outdoor air temperature does not exceed +8°C.

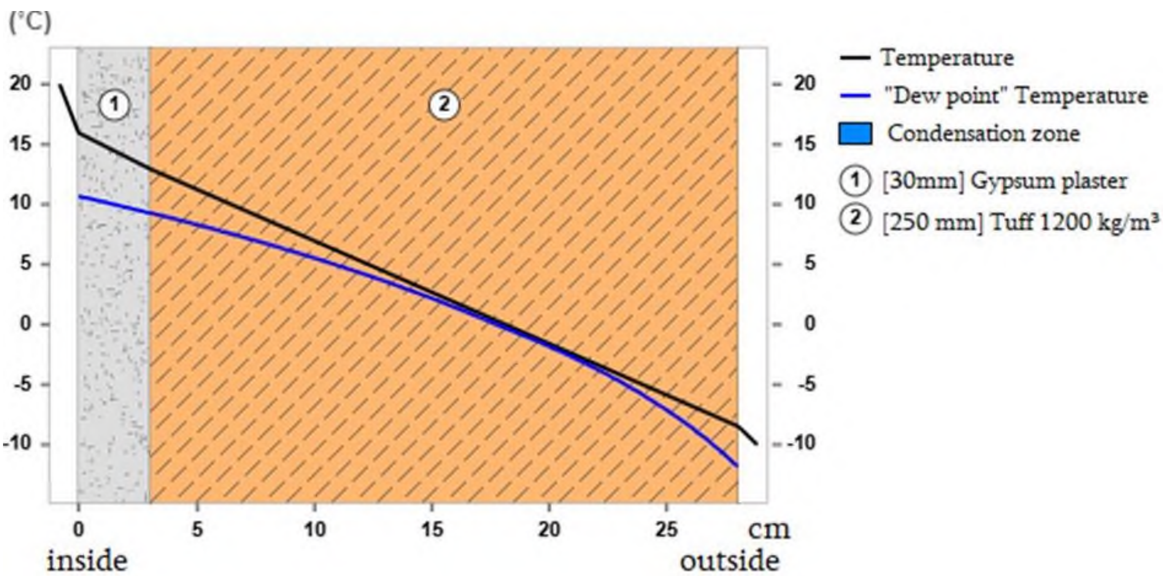

Fig. 2. *External cladding structure before thermal insulation*

Due to the variation in outdoor climatic conditions across different months, the building's thermal losses—calculated based on design temperature and vapor permeability—amount to 17.0 kW for Sisian. Below (Table 1), the fuel consumption during the heating season is presented according to different temperature regimes [7-9].

Table 1. Fuel consumption by temperature regimes

Cities	Fuel consumption during the season according to the 80/60 ^{O}C temperature regime, m^3/season	Fuel consumption during the season according to the 60/40 ^{O}C temperature regime, m^3/s	Fuel consumption during the season according to the 45/25 ^{O}C temperature regime, m ^{3}/season
Sisian	2464	2551	2496

Results and Discussion

After determining the seasonal fuel consumption for the building without thermal insulation, calculations were performed to identify the optimal thermal insulation material and layer thickness for the building, taking into account local climatic conditions, external structures, and other relevant factors [10]. Based on the results of these calculations, polyurethane (PU) was selected as the optimal thermal insulation material [11].

Following the initial data collection, in the second half of the experimental phase, the exterior walls and roof of the building were insulated with polyurethane foam (PUF) to ensure thermal stability under various seasonal conditions. In the mid-stage of the study, the complete external insulation of the building was carried out [12,13]. The materials used and the implemented steps are shown in Figure 3**.**

Insulation material – 50 mm thickness with a ±10 mm tolerance, density of 35–40 kg/m³, thermal conductivity coefficient of 0.022 W/m·°C.

Installation – The polyurethane (PU) was sprayed using a specialized device, followed by the application of a reinforcing mesh made of glass fiber and a finishing plaster layer.

Roof insulation – The polyurethane foam (PUF) was sprayed onto the roof covering.

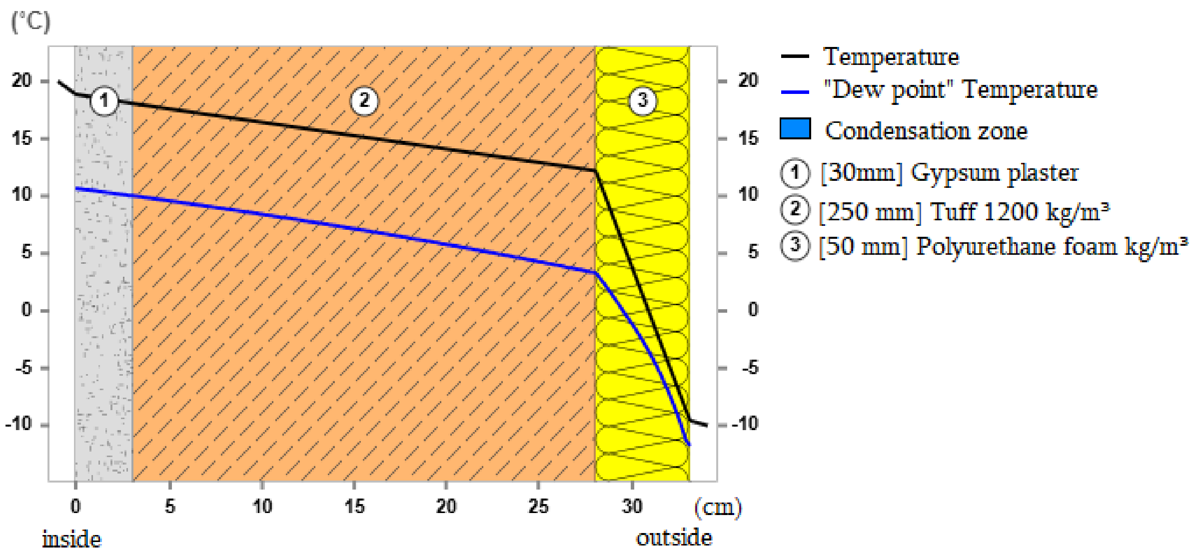

Fig. 3. *External cladding structure before thermal insulation*

By implementing thermal insulation on the building's external enclosing structures, an improvement in the thermotechnical parameters of the external wall (enclosure) is achieved, specifically reducing the thermal transmittance coefficient (U-value) to 0.34 W/m²·°C.

The finishing plaster layer (μ = 15-25) provides significantly higher vapor permeability than the polyurethane foam core (μ = 30-60), allowing moisture migration from interior to exterior while preventing water infiltration. This permeability gradient prevents moisture accumulation within the wall assembly, which is critical for cold-climate applications where freeze-thaw cycles could compromise insulation performance. The 50 mm PUF thickness was selected based on economic optimization studies, balancing diminishing thermal returns against material and installation costs for the Syunik region climate.

Based on these changes, a recalculation of the gas consumption during the heating season has been performed.

The fuel used is natural gas, methane. Armenia is highly dependent on natural gas as the main energy source for heating residential buildings, as about 95% of households in urban areas are connected to a centralized gas distribution network. The country imports natural gas mainly from Russia through the North-South gas pipeline system, supplemented by limited domestic production and agreements with Iran for the southern regions. Natural gas is preferred due to its relatively low cost compared to electricity, its cleaner burning characteristics compared to solid fuels (coal, wood), and the established infrastructure in populated areas. In Sisian and other settlements in the Syunik region, natural gas is supplied with a standard calorific value of approximately 8,500 kcal/m³ (35.6 MJ/m³), making it the most efficient and affordable heating option for residential buildings. In this study, fuel consumption measurements (m³/season) are directly related to household energy costs, as natural gas pricing in Armenia follows government-regulated tariffs, which account for about 15-25% of average household utility costs during the heating season in mountainous regions [14].

Table 2. Fuel consumption according to temperature regimes

Cities	Fuel consumption during the season according to the 80/60 ^{O}C temperature regime, m ^{3}/season	Fuel consumption during the season according to the 60/40 ^{O}C temperature regime, m ^{3} /s	Fuel consumption during the season according to the 45/25 ^{O}C temperature regime, m ^{3} /season
Sisian	1066	1106	1082

By comparing the data in Table 1 and Table 2, we obtain the gas consumption comparison graph in Figure 4, which shows a comparison of fuel consumption during the season according to the temperature regime of the building before thermal insulation and after thermal insulation [15].

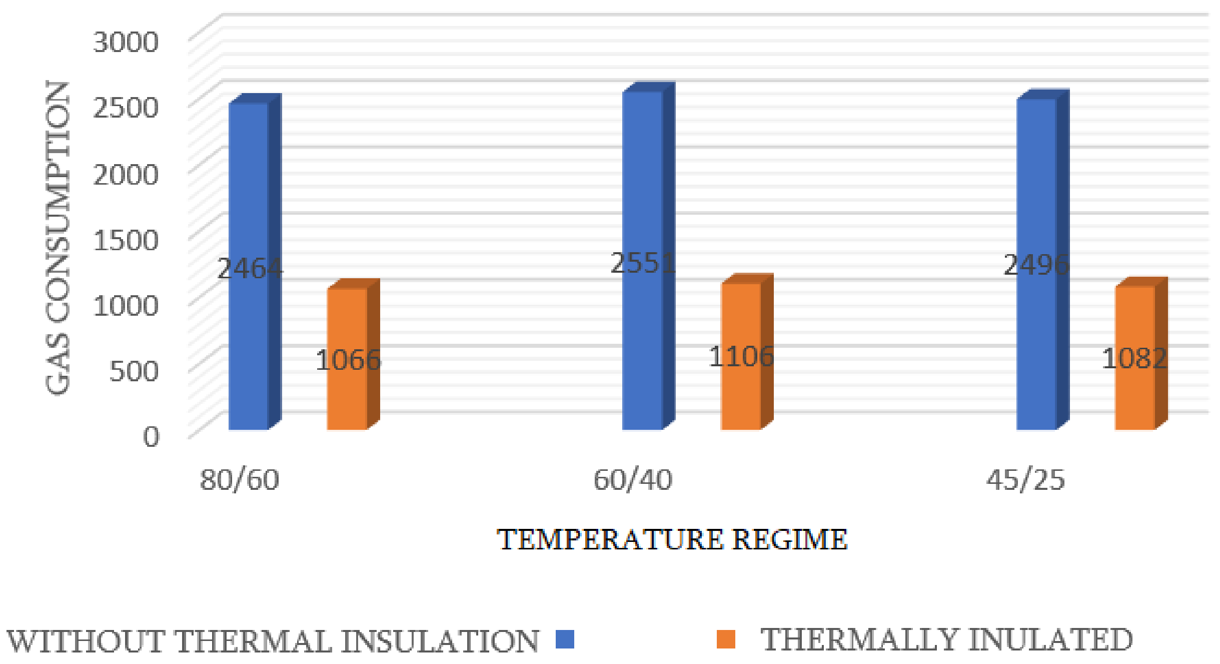

Fig. 4. *Seasonal fuel consumption comparison graph*

Conclusion

- The 2.3-fold fuel reduction at 1,600m elevation indicates a critical insulation threshold exists for high-altitude buildings. Below 50mm polyurethane foam thickness, energy losses increase exponentially due to prolonged heating seasons and extreme temperature differentials specific to mountainous regions.
- The use of thermal insulation material in the external envelope construction neutralizes the condensation zone, which increases the heating load and affects the strength of the building.
- The reduction in gas consumption from 2,464 to 1,066 m³/season proves that the renovation of tuff stone buildings is economically viable. This model applies to 70% of Armenia's housing stock, which could potentially reduce national gas imports by 15-20%.

Conflict of Interest

The author declares no conflicts of interest.

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References

[1]. H. Huakun, Z. Yijun, H. Renda, W. Huijun, S. Yongjun, H. Gongsheng, X. Tao, Optimum Insulation Thicknesses and Energy Conservation of Building Thermal Insulation Materials in Chinese Zone of Humid Subtropical Climate. Sustainable Cities and Society, 52, 2020, 101840. Doi: https://doi.org/10.1016/j.scs.2019.101840

[2]. A. Kitous, J. Després, Assessment of the Impact of Climate Change on Residential Energy Demand for Heating and Cooling. Publications Office of the European Union, 2018. Available at: https://surl.li/sqadyy. Accessed on July 10, 2025

[3]. H. Lee, J. Romero, Summary for Policymakers, in: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland. Doi: https://doi.org/10.59327/IPCC/AR6-9789291691647.001

[4]. B. Abu-Jdayil, A. Mourad, W. Hittini, M. Hassan, S. Hameedi, Traditional, State-of-the-Art and Renewable Thermal Building Insulation Materials: An Overview. Construction and Building Materials. 214, 2019 709–735. Doi: https://doi.org/10.1016/j.conbuildmat.2019.04.102

[5]. D. Kumar, M. Alam, P.X.W. Zou, J.G. Sanjayan, R.A. Memon, Comparative Analysis of Building Insulation Material Properties and Performance. Renewable and Sustainable Energy Reviews, 131, 2020, 110038. Doi: https://doi.org/10.1016/j.rser.2020.110038

[6]. A.M. Papadopoulos, State of the Art in Thermal Insulation Materials and Aims for Future Developments. Energy and Buildings, 2005, 37 (1), 77-86. Doi: https://doi.org/10.1016/j.enbuild.2004.05.006

[7]. X. Meng, B. Yan, Y. Gao, J. Wang, W. Zhang, E. Long, Factors Affecting the in Situ Measurement Accuracy of the Wall Heat Transfer Coefficient using the Heat Flow Meter Method. Energy and Buildings, 86 (4), 2015, 754-765. Doi: https://doi.org/10.1016/j.enbuild.2014.11.005

[8]. M. Ozel Cost Analysis for Optimum Thicknesses and Environmental Impacts of Different Insulation Materials. Energy and Buildings, 49, 2012, 552-559. Doi: https://doi.org/10.1016/j.enbuild.2012.03.002

[9]. A. Petrosyan, S. Sargsyan Moisture Protection of Residential Buildings Influence of Tynes on the Thermal-Humidity Regime of the Building. Journal of Architectural and Engineering Research, 8, 2025, 3-11. Doi: https://doi.org/10.54338/27382656-2025.8-01

[10]. J. Wyrwa, A. Marynowicz. Vapour Condensation and Moisture Accumulation in Porous Building Wall. Building and Environment 37 (3), 2002, 313-318. Doi: https://doi.org/10.1016/S0360-1323(00)00097-4

[11]. S. Walker, Scottish House Condition Survey. Energy use in the Home - Measuring and Analysing Domestic Energy use and Energy Efficiency in Scotland. Scottish Government, 2012.

[12]. B.P. Jelle, Traditional, State-of-the-Art and Future Thermal Building Insulation Materials and Solutions – Properties, Requirements and Possibilities. Energy and Buildings, 43 (10), 2011, 2549-2563. Doi: https://doi.org/10.1016/j.enbuild.2011.05.015

[13]. Hussein Akeiber, Payam Nejat, Muhd Zaimi Abd. Majid, Mazlan A. Wahid, Fatemeh Jomehzadeh, Iman Zeynali Famileh, John Kaiser Calautit, Ben Richard Hughes, Sheikh Ahmad Zaki, A Review on Phase Change Material (PCM) for Sustainable Passive Cooling in Building Envelopes. Renewable and Sustainable Energy Reviews, 60, 2016, 1470-1497. Doi: https://doi.org/10.1016/j.rser.2016.03.036

[14]. R. Dylewski, J. Adamczyk, Economic And Environmental Benefits of Thermal Insulation of Building External Walls. Building and Environment, 46 (12), 2011, 2615-2623. Doi: https://doi.org/10.1016/j.buildenv.2011.06.023

[15]. F. Ascione, N. Bianco, R. Francesca De Masi, G.M. Mauro, G.P. Vanoli, Energy Retrofit of Educational Buildings: Transient Energy Simulations, Model Calibration and Multi-Objective Optimization Towards Nearly Zero-Energy Performance. Energy and Buildings, 144, 2017, 303-319. Doi: https://doi.org/10.1016/j.enbuild.2017.03.056

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STUDYING THE ARCHITECTURE ELEMENTS OF SUBURBAN CARAVANSERAIS IN CENTRAL IRAN TO IDENTIFY THEIR SIMILARITIES AND DIFFERENCES

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Abstract: *This study explores how the architecture of Iranian caravanserais evolved due to changes in architectural knowledge, techniques, and functional needs. The main goal is to classify and compare the physical and architectural features of caravanserais in central Iran to identify their common and distinctive characteristics. The research addresses one main question: How do physical and metaphysical factors influence the formation of architectural styles?. Using a developmental and applied approach, the study combines inductive, interpretive, historical, and comparative methods. Data were collected through library research and field observations. Key architectural components—such as entrances, vestibules, porches, courtyards, rooms, porticos, stables, and towers—were analyzed in terms of spatial organization and typology. Findings show that caravanserai architecture was shaped by the construction traditions and design systems of its time, following shared frameworks created by skilled architects and coordinated institutions. By comparing architectural features, the research identifies which elements remained consistent and which evolved, offering valuable insights for the conservation and restoration of damaged caravanserais. The study focuses on roadside caravanserais in Isfahan, Qom, Markazi, and Tehran provinces, analyzing 65 examples from various historical periods in Iran's hot and dry central regions.*
Keywords: *architecture elements, physical typology of caravansary, commonalities and differences of caravansary, restoration and conservation of caravansary, suburban caravansary in central Iran..*

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Introduction

Caravanserais are generally classified into two main types: urban and rural (or roadside). Since the focus of this study is on outer-city (rural) caravanserais, the architectural characteristics of urban caravanserais are mentioned only for definitional purposes. Like other historical structures, caravanserais consist of various architectural elements and components that together form a unified identity. The entrance system may be single- or double-storied and can either project outward, recede inward, or align with the main façade. Beyond the entrance lies a vestibule, typically square or polygonal in shape, which serves as a transitional space determining access to other areas.

Following the vestibule, a long corridor usually leads to a porch, which then opens into a central courtyard—a key spatial feature that can be square, rectangular, or polygonal. This courtyard provides access to verandas, chambers, and stables, which are arranged around it. The chambers are typically fronted by verandas, while the stables occupy the outermost ring of the complex. Inside the stables, docks, and raised platforms are commonly found, and shepherds' rooms are often located near the stable entrances.

Externally, caravanserais resemble fortified castles, characterized by strong towers and ramparts. Some were equipped with windcatchers (badgirs) for natural ventilation and thermal balance. Water was supplied through ponds, reservoirs, qanats, or nearby springs [1,2].

In this research, the physical typology of caravanserais is analyzed based on the spatial composition of their principal architectural elements and examined across different historical periods. The arrangement and interrelation of these elements, whether present, absent, or spatially modified, form the basis of their typological differentiation.

In addition to the main elements, some caravanserais also include secondary components, which vary from one structure to another. The formation of both primary and secondary elements has been influenced by a range of physical and metaphysical factors—including climatic, cultural, social, political, religious, technical, and structural considerations.

Depending on the facilities provided, caravanserais are categorized into three types:

1. Simple caravanserais, consisting solely of the main structure,
2. Intermediate caravanserais, which include an external but independent water tank,
3. Combined or complex caravanserais, integrating additional features such as gardens, baths, mosques, bridges, water mills, and reservoirs.

The architectural patterns of caravanserais evolved gradually under the influence of these diverse factors. Social, climatic, cultural, religious, structural, and economic conditions all contributed to shaping their designs. Initially, early caravanserais lacked stables or watering facilities, but as travelers' needs grew, their architectural diversity expanded in form, geometry, proportion, and function.

Throughout history, every architectural element of caravanserais has transformed. The creativity of architects, the functional requirements of travelers, and the economic capacities of patrons—whether rulers, benefactors, or wealthy individuals—collectively fostered remarkable variety in design.

Architectural plans from different periods reveal both diversity and evolution. During the early Islamic centuries (up to the 4th century AH), the architectural form remained close to pre-Islamic prototypes. The major evolution occurred in the Seljuk era, reaching its peak during the Safavid period.

Typical Safavid caravanserais featured a prominent entrance (often with one or two stories), a quadrangular or octagonal vestibule, and a long corridor leading to a porch that opened into a central courtyard surrounded by rooms. Behind these rooms were camel stables, accessible from the courtyard. The exteriors included watchtowers, high walls, and outer verandas.

After the Safavid era, caravanserai architecture experienced only minor stylistic changes, with most designs adhering to established layouts.

This study aims to analyze and explain the typology of the key architectural elements of caravanserais—namely, the entrance, veranda, central courtyard, porch, rooms, front verandas, stables, and towers. The research focuses on the spatial composition and interaction of these core components within the overall architectural plan.

Research Question

How do physical and metaphysical components affect the formation of architectural designs and types?

Literature Review

In one article, researchers have studied the emergence and evolution of caravanserais architecture throughout history and have introduced the details of the architecture and structure of caravanserais by presenting maps and documentary evidence. In this article, the process of changes in caravanserais attributed to the Sassanid, early Islamic, Seljuk, Ilkhanid, Safavid, and Qajar periods has been examined, and the major changes that have occurred in them have been graphically depicted [3].

In another article, the researcher of the article studied the structure of Safavid-era caravanserais, identified the origin of the formation and conceptual terminology of caravanserais, and compared the architecture of caravanserais. In this article, the author studied the Safavid caravanserais of the central plateau of Iran and compared their plans and architectural characteristics. The author deals with the anatomy of caravanserais and studies the physical, architectural, organizational, main axes, and full and empty spaces of the caravanserais by presenting graphic maps and images. He examines the elements and components of the caravanserais, such as the entrance, the porch corridor, the private part, the stable, and the stables of the room. In another part of the anatomy of caravanserais, the author introduces several examples of the Safavid caravanserais under study and applies his practical analysis to caravanserais such as Aminabad, Madar Shah, Mazinan, and Mehr, and reviews their full and empty spaces, main axis, symmetry, main form, and area [4].

Another article has compared the proportions governing the architecture of courtyard caravanserais in central Iran during the Safavid and Qajar periods. The authors of the article have first examined the history of the emergence of the caravanserais, defined their terminology, and examined their historical developments over time from the Achaemenid period to the Sassanid period. In the second part of the article, the authors have examined the role of the caravanserais in Iranian-Islamic civilization and have researched the evolution of caravanserais in the Islamic period and have outlined and described their evolution by presenting plans. In the following article, the authors have introduced study examples. In this statistical population, three categories of Iranian caravanserais were selected, such as caravanserais in hot and dry regions, mountainous regions, and the Persian Gulf coast. In this article, the emphasis and focus are on courtyard caravanserais in the central regions of Iran. In this research, the characteristics of the length and width of the rooms, courtyards, and entrances, and their ratio to each other have been examined. In this research, the architectural structure and its details have been seen and fully introduced [5].

In a book, researchers have studied the history, history of the emergence, and architectural stylistics of caravanserais and have examined the evolution of caravanserais. The authors of this article have examined the historical course of caravanserais from the pre-Islamic period and from the Achaemenid period to the Islamic period, and in the Islamic period, they have also researched the course of their emergence and development from the early Islamic period to the Qajar period. They have also studied and read the functions of caravanserais. They write about the caravanserais of Isfahan in the Safavid period: The most extensive and prosperous commercial function of the Safavid caravanserais was in the international commercial city of Isfahan, a city where not only political affairs but also all economic activities ended [6].

Another work has studied the architectural elements of the entrance spaces of the Safavid caravanserais of Khorasani Razavi. The authors of the article initially examined and defined the elements and components of the entrance and examined the course of their development in the caravanserais of Khorasan. In this article, the authors have examined the form of the caravanserais' entrances in the introduced statistical population. They have examined the entrance system and their hierarchy, and the form of the entrance has been further clarified by presenting images and graphic maps [7].

Another article has reviewed the physical characteristics of Sabzevar caravanserais during the Safavid period. In the first step, the authors have discussed the transformation and evolution of the caravanserais in Iranian architecture. By examining the historical course of the Iranian caravanserais from the pre-Islamic period to the Islamic period, the authors have reviewed the changes in the plan, form, and shape of the caravanserais and the changes that have occurred in each period. In the next step, the authors have categorized the caravanserais and studied them in terms of climate, architecture, and functionality. In the next section, the authors discuss the multiple functions of the caravanserais and specify their functions. In the next step, the authors introduce the presented caravanserais on a case-by-case basis. This introduction is accompanied by a map and image, and they have studied and reviewed their architectural features and spatial organization, length, width, and area [8].

Another study examined the impact of understanding the different causes and factors in the formation and organization of the Iranian caravanserai. The author of the article first examined the buildings of caravanserais and the historical course of their emergence in the pre-Islamic period and briefly examined similar buildings such as Robat, Chaparkhaneh and Sabat. Next, the author of the article studied the climatic course of Iranian caravanserais and reviewed the classification presented by Kiani and Klais. In fact, the author studied the physical evolution of Iranian caravanserais throughout history, and he considers the emergence of caravanserais in the Achaemenid period and considers Chaparkhanehs that were located on the royal road and main roads to be the first example and type of caravanserais. The author considers climate and weather conditions to be the main factors in determining the materials used in caravanserais and considers this a characteristic of Iranian architecture. The author concludes that the form and plan of the caravanserais are more subject to rules and laws than other buildings and that their form is usually square or rectangular and has guard towers at the entrance and on the top. The caravanserais are called Shetarkhan, and they had stables, and the layout of the spaces has not changed much over time, and most of the caravanserais have four porches, and brickwork, plasterwork and tilework decorations have been used on the surface of the walls [9].

A researcher has studied the origin and history of caravanserais in a study and has categorized them and divided them into two categories: urban and rural (wayside) caravanserais. He studies Iranian caravanserais on a case-by-case basis and introduces some of the important caravanserais. The author of the above book has visited most of the Iranian caravanserais and has also taken and drawn their maps. In this article, he examines the caravanserais and the characteristic ropeways of each historical period. In this book, the author has studied the process of formation of caravanserais from the pre-Islamic period to the Qajar period. Most of the maps presented in this book are among the first documentaries about caravanserais in Iran. The positive advantage of this book is the presentation of accurate and reliable maps and explanations [10].

Twenty years later, in another book, the same author has examined the historical roads of Isfahan province and their routes and has introduced the buildings related to them, such as caravanserais, in full. In this article, the author introduces the inner and outer caravanserais of Isfahan and examines the reasons for the emergence of caravanserais in this region. He presents a plan and a photo to introduce each caravanserais so that the reader's vision is broadened and their understanding of the subject becomes more tangible. He also reviews the documents that travelers have written about caravanserais by referring to historical texts [11]. These two books are among the first valuable research on caravanserais.

Other researchers have studied the spatial physical typology of the out-of-town caravanserais on the Isfahan-Ray and Saveh road network based on the spatial composition of the rooms and stables of the caravanserais. In this study, the authors of the article have presented patterns by examining the stables and rooms of the caravanserais and how they are arranged in the architectural plan. In the above study, only the two elements of the stable and the room have been typified, and the other main elements have not been examined. Considering the background of the presented research, it can be said that there have been studies on the typology of the architectural elements of the caravanserais in the studied area, but the studies have been limited to one region. This study examines the caravanserais in several different regions, and this type of article is in the field of typology [12].

However, no independent research has been conducted on the similarities and differences of the caravanserais in the studied area. And the present study tries to address this issue for the first time.

Research Methodology

The present study is analytical and descriptive. The main method of collecting information is based on library studies, studying architectural plans, and field impressions. The approach to data analysis is interpretive, historical, and comparative. The sampling method is purposive (non-probability). The statistical population of this study includes intact and ruined caravanserais in the central regions of modern Iran. In this study, 65 caravanserais were selected from the caravanserais in the central regions of Iran for the study. The studied caravanserais cover the regions of Isfahan, Yazd, Qom, Tehran and Markazi (Table 1). The sample caravanserais include a variety of geographical, spatial, and historical features and typologies. The data were initially raw, but with interpretive, historical, and comparative analyses of the architectural elements of the caravanserais, they were reread and categorized, and then by comparing the categories and architectural indices of the samples one by one, the patterns were explained, and finally, by comparing them with each other, the similarities and differences were explained. The limitations of the present research are the lack of maps and documented information on some elements and components, such as the entrance device, the gate, the stable, and the room of the ruined and damaged caravanserais, and the incorrect past restorations in the remaining and lost parts of the caravanserais. The method of overcoming limitations includes field observations, documentary photography, extraction of information and library documents, and comparison of similar caravanserais in the same cultural area.

Result

Introduction to the main elements of caravanserais (Table1)

Entrance**:** The entrance in caravanserais has 4 types: 1- The entrance surface is flush with the exterior. 2- The entrance is prominent and protrudes from the exterior. 3- The entrance is recessed and hollowed out from the exterior. 4- The entrance protrudes from the exterior, but its corners are chamfered. In the example of the first type, we can refer to the Pasangan and Yangi Imam caravanserais, which are attributed to the Safavid period, and the Haj Kamal caravanserais, which are attributed to the Qajar period. The entrances of the early caravanserais were one-story and did not have an upper house, but in later periods, such as the Safavid and Qajar periods, the entrances were two-story and had an upper house. For the second type of entrance, we can refer to the Deirgachin, Gabarabad, and Tor caravanserais. For the third type of entrance, we can refer to the Mahyar caravanserais. In the fourth type of entrance with 45-degree bevels, we can mention the caravanserais of Jolegir, Natanz, Hasanijeh, Morche Khorat, Hajib, and San San. Usually, there were arches next to the entrance of the caravanserais, which were sometimes decorative arches. Caravansers with two-story entrances usually had an opening called a lead thrower, which was used to pour hot lead on attackers in times of danger. Usually, there was a stone and brick inscription at the entrance of the caravanserais, in which the name of the founder, builder, date of construction, and the name of the architect of the caravanserais were mentioned. The entrance of the caravanserais was the most decorated and beautiful part of the caravanserais. The entrance was usually higher than the adjacent levels. Sometimes the entrances were high and sometimes wide.

Hallway**:** The communication space between the vestibule and the porch is called a hallway. The roof of the corridor is usually covered with a barrel vault. The corridors were usually long spaces and extended to the outer edge of the courtyards. In some caravanserais, there is a platform on the sides where the caravans can temporarily sit and stand to watch the space inside the caravanserais. The platforms are usually 60 cm high. And their materials are made of stone and brick. Examples of platform corridors of caravanserais include the Deirgachin and Aveh caravanserais.

Vestibule**:** The vestibule is the entrance ring connecting the other spaces of the caravanserais. The vestibule is usually quadrangular or octagonal. Vestibules usually have a domed roof, and there are guard chambers on two sides. Vestibules are usually higher than the ground level, and connection with the guard chambers is possible via stairs. In some caravanserais, access to the camel stalls was possible through the vestibule, and on the sides of the vestibule, there were two doors to the left and right camel stalls, such as the caravanserais of Yengi Imam and Zayn al-Din. On the sides of the octagon, or quadrangle, there are rows of stairs to access the roof, such as the caravanserais of Hajib, Jalogir, Deirgachin, and San San. The width of these stairs was usually 1 meter. The octagons usually had a platform on which people could sit. There are false arches on the vestibule wall that have a decorative role.

Towers and ramparts**:** Due to their location in desert, mountainous, and desert areas and away from urban centers, suburban caravanserais need guard towers at the corners of the caravanserais to ensure their security. These towers are usually circular and made of stone and brick. The towers are usually higher than the ramparts and have crossbows for shooting. Among the caravanserais with towers, we can mention the caravanserais of Hajib, San San, Deirgachin, Nogonbad, and Pasangan. In the Safavid period, in order to ensure the relative security of the roads and the country, and considering the location of the caravanserais, caravanserais were usually designed without towers, such as the caravanserais of Yengi Imam and Haj Kamal.

Chamber: Chambers in suburban desert caravanserais are located around the central courtyard and are usually higher than the ground level so that dust, rainwater, and animals cannot enter them. Chambers have a small veranda in front of them, and access to the rooms is through this veranda. The rooms have a fireplace and a stove, and their light is provided either through a horno in the ceiling or through the entrance door of the room. The rooms usually do not have an entrance door, and curtains are used instead. The ceiling of the rooms is usually a curved arch, such as a cradle arch or a four-part arch. The heat of the rooms is also provided by burning shavings and firewood. In mountain inner-city caravansaries, the rooms are usually located around a central hall. In mountain caravansaries, the caravansaries are covered and roofed. In such caravansaries, the spaces are lower than the ground level to use the heat of the earth. The exterior of the rooms and verandas was decorated with pedimented arches. Some caravansaries had a porch in front of their rooms, but this type of design was not common in caravansaries. Usually, there were enclosures for animals in the outer side courtyards facing the caravansary courtyard. The caravanserai of Wardeh-e-Saveh has no rooms, and there are only verandas around the courtyard for travelers to rest.

Camel House (stable): Camel houses were designed around the outermost layer of the caravanserai. The stables are usually located behind the rooms, and the outermost layer of the caravanserai is against its perimeter wall. The camel houses have platforms and docks on both sides or on one side so that they can unload the animals. Sometimes the guard and the animal handler would stay on these platforms and spend the night. The roof of the camel houses is vaulted and domed. Part of the heat of the rooms was also provided through the camel houses. Access to the camel stalls was either in the vestibule area and on the sides of the vestibule, or through the central courtyard, and the path was taken from the corners of the central courtyard. The central courtyard of the caravanserai was either rectangular or octagonal, and access to the camel stalls was possible through one of the small sides of the octagon or the corners of the rectangular square. Heating of the interior of the camel stalls was provided by burning firewood. In the camel stalls, a small opening with a stone or a cylindrical wooden rod inside was used to close the animals. Light inside the camel stalls was provided through the opening in the roof dome (horno).

Porch: Caravanserai have four porches on their four sides. These porches are higher than the ground level and have a fireplace and a ledge. Some porches of caravanserai have steps so that the porch can be accessed from the floor of the courtyard. The dimensions and size of the porches are larger than the rooms of the caravanserai. Usually, the height of the porches is also higher than the height of the rooms next to them. The porches are usually long and deep. Sometimes the porches have the role of a royal residence and are divided into two longitudinal parts. The first part had a more public role, and the second part, which had the form of a post, was more private. The access road from the first part to the inside was through not very high doorways. The porches were usually decorated with rich decorations, such as brickwork with a sleeping and upright design.

Verandas on the exterior and interior of the caravanserai: Caravanserais usually had several platforms and verandas on their exterior that were used for temporary rest of the caravans. In some cases, these verandas served as rooms, and a few people could rest on the platforms and spend the night. Usually, there were fences and pens for tying animals next to or below these platforms.

Central court yard: Iranian caravanserais had a central courtyard, depending on their geographical and surrounding environment. The shape of the courtyards was usually square, rectangular, circular, or octagonal. The octagonal courtyards were usually octagonal and half- octagonal, not completely octagonal, and the octagonal chamfers were small. And in the course of the development of caravanserais architecture, this small chamfer later became the access point to the stables. Circular caravanserais also had circular courtyards, such as the Zizeh and Zein al-Din caravanserais and Taj Abad in Hamedan. In octagonal caravanserais, such as Amin Abad, the inner space of the courtyard was also a regular octagon of the same size. In the central courtyard of the caravanserais, there were enclosures for tying animals. In early caravanserais, there was usually no camel house space, and the miansarais also played the role of a stable.

Table 1. Main architectural elements of caravanserais (Authors, 2025)

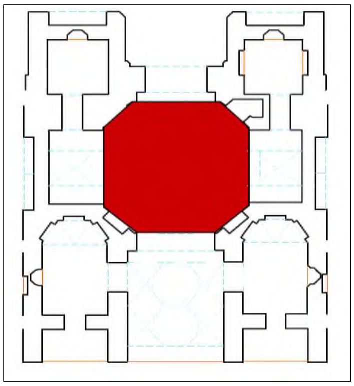
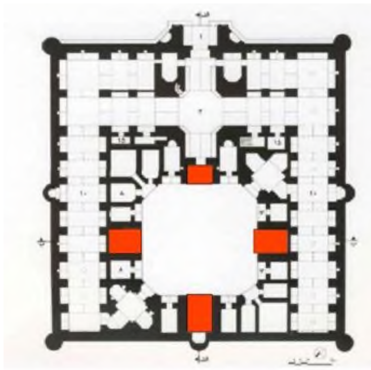
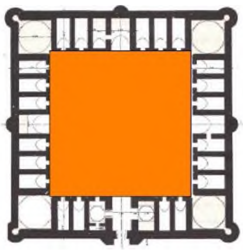
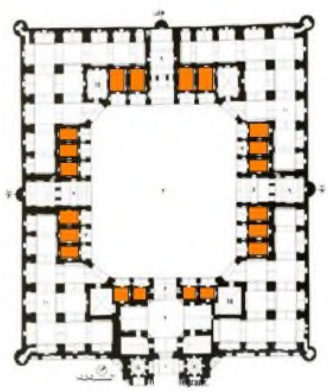
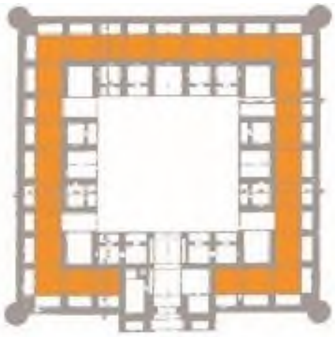
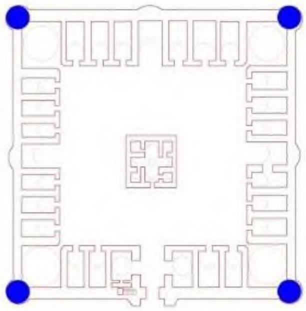
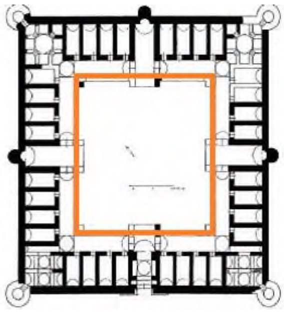
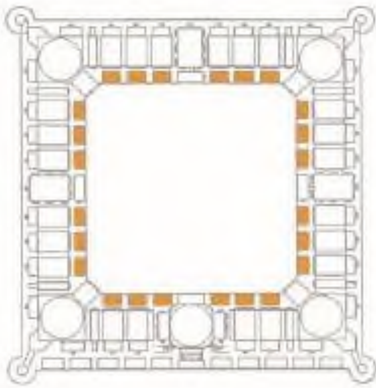
N	Title	Picture	Plan
1	Entrance		
2	Vestibule and hallway		
3	Porch		
4	Central court yard		
5	Chamber		

Table 1 (continued)

6	Stable		
7	Tower		
8	Portico		
9	interior veranda		
10	exterior veranda		

Commonalities and Differences of the Caravanserai in this area

After categorizing and analyzing the findings in this section in order to find the commonalities and differences of the caravanserai by historical period, based on the research findings, the caravanserai of each period were studied comparatively, and the similarities and differences of their elements and components were explained. Next, in order to clarify the evolution of the caravanserai, the commonalities and differences of the elements and components of the caravanserai were compared and examined with respect to their historical periodization, and then their general similarities and differences were explained by combining the historical periods (Tables 2 and 3). Seljuk caravanserai often had a portico, four porches, solid circular towers, and a prominent entrance, and they lacked a vestibule and instead had a corridor. The rooms were rectangular, and the caravanserai did not have a veranda in front of the rooms. Seljuk caravanserai did not have a veranda on the exterior. Seljuk caravanserais often have four-sided spaces in their corners and a central pavilion in the middle of the courtyard, which often plays the role of a royal residence. In Ilkhanid caravanserais, the portico element gradually gives way to a veranda. The rooms in Ilkhanid caravanserais are square, and the evolution of the rectangular room of the Seljuk caravanserais is the one. Ilkhanid caravanserais have a corridor at the entrance, and a vestibule space is also taking shape. The towers in Ilkhanid caravanserais are solid and circular. Another change in Ilkhanid caravanserais is the creation of a special space for caravan owners, which is located in the corner of the caravanserais and at the entrance of the camel khans. Another change in Ilkhanid caravanserais is the creation of the camel khan behind the rooms and in the last ring. Ilkhanid caravanserais do not have a veranda on their exterior. The main building in Seljuk, Ilkhanid, and Timurid caravanserais is one-story. In Timurid caravanserais, the camel sheds behind the rooms and towers are round, hollow, and solid. The rooms in Timurid caravanserais are mostly square. Safavid caravanserais are an evolved form of their previous caravanserais. The hierarchy of access is completed in the caravanserais of this period. The veranda space is added to the exterior of the caravanserais. The latrine is seen in the caravanserais of this period. The caravanserais of this period have a private space for the king. There is a veranda in front of the rooms. The design of an independent water tank outside the caravanserais is more visible in this period. The general geometric shape of the caravanserais in the Seljuk caravanserais is square; in the Ilkhanid and Timurid caravanserais it is square and octagonal; in the Safavid caravanserais it is a full octagon, a jewel octagon, and a quadrangle; in the Qajar caravanserais it is octagonal and circular, a quadrangle, and an octagon; and in the Qajar caravanserais it is also a quadrangle. The geometric shape of the courtyard is also a quadrangle in the Seljuk and Ilkhanid caravanserais. Considering the above, it can be said that the climate, cultural, and technical factors and the period of construction have played a colorful role in the design and formation of the architectural patterns of the caravanserais. But it can be said that the climate has played the greatest role in the design of the caravanserais (Tables 2 and 3). In addition to causing the emergence of diverse patterns in different historical periods, even in each historical period, it also causes the formation of numerous patterns.

Table 2. Commonalities and differences between caravanserais based on historical period (Authors, 2025)

Historical Period of Caravanserai	Similarities	Differences
Sassanid	Has an entrance. Has a corridor. Has a room. Has a porch. Has a camel house. Has a courtyard. Has a tower. The Deirgachin Caravanserai is the only study example attributed to the Sassanid period in this research and was transformed during the Safavid period.	-
Seljuk	Has an entrance. Has a corridor. Has a porch. Has a room. Has a portico. Has a camel house. Has a courtyard. Has a tower. Has no veranda on the exterior.	The Koh Namak Caravanserai has a vestibule and no corridor. The Dehchi caravanserai does not have a portico and has a veranda in front of the room. The old Chaleh Siah Khohneh and Tarlab caravanserai do not have towers.
Ilkhanid	They have a corridor. They have a porch. They have rooms They do not have a portico. They have a camel house. They have a courtyard. They have a tower. They do not have a veranda on the exterior. They have a veranda in front of the room.	The Chahar Abad caravanserai does not have a tower.
Safavid	They have a corridor and a vestibule. They have a porch. They have rooms. They have a veranda. They do not have a portico. They have a camel house. They have a courtyard. They have a tower. They have a veranda on the exterior.	Some caravanserais do not have a tower. Some caravanserais do not have a veranda on the exterior. Some caravanserais do not have rooms (Pasangan and Vardeh). Some caravanserais do not have a veranda in front of the room. Some caravanserais have both a vestibule and a hallway, and some have either a vestibule or a hallway.

Table 2 (continued)

Qajar	They have a hallway and a vestibule. They have a porch. They have rooms. They have a porch. They do not have a portico. They have a camel house. They have a courtyard. They have a tower. They have a veranda on the exterior.	Some caravanserais do not have a tower. Some caravanserais do not have a veranda on the exterior. Some caravanserais do not have a room (Dalak caravansarai). Some caravanserais do not have a veranda in front of the room. Some caravanserais have both a vestibule and a hallway, and some have either a vestibule or a hallway

Table 3. Commonalities and differences between caravanserais based on the intertwining of historical periods (Authors, 2025)

Title	Description
Similarities	Sassanid, Seljuk, Ilkhanid, Safavid and Qajar caravanserais have rooms. Some Sassanid, Ilkhanid, Safavid and Qajar caravanserais have a veranda in front of the rooms. Caravanserais have an entrance. Caravanserais have a camel house. Caravanserais have porches. Caravanserais have courtyards. Caravanserais have towers. Seljuk caravanserais do not have verandas in front of the rooms. Ilkhanid, Safavid and Qajar caravanserais have verandas on the exterior. The entrance system of Sassanid caravanserais includes an entrance, a hallway. The entrance system of Seljuk caravanserais includes an entrance, a hallway. The entrance system of Ilkhanid caravanserais includes an entrance, a hallway. The entrance system of Safavid caravanserais includes an entrance, a hallway. The entrance system of Safavid caravanserais includes an entrance, a hallway. The entrance system in Qajar caravanserais includes a main building, a vestibule, and a hallway. Most Safavid caravanserais have a tower. Most Qajar caravanserais have a tower. Sassanid, Safavid, Ilkhanid, and Qajar caravanserais have no portico. Seljuk and Ilkhanid caravanserais do not have a veranda on the exterior. Sassanid, Seljuk, Ilkhanid, Safavid, and Qajar caravanserais have a single-story entrance.
Differences	The Seljuk caravanserais have a portico. Some Seljuk (2 examples), Ilkhanid (1 example), Safavid, and Qajar caravanserais do not have a tower. Some Safavid and Qajar caravanserais do not have a veranda on the exterior. Two examples of Safavid (Vardeh and Pasangan) and one example of Qajar (Pol-e-Dalak) caravanserais have no rooms. One example of Seljuk caravanserais has a vestibule instead of a corridor. One example of Qajar caravanserais (Baqerabad) and one example of Seljuk caravanserais (Robat Sangi Natanz) do not have a main building. One example of Seljuk caravanserais (Dehchi Morche Khoret) has a veranda in front of the room and does not have a portico. The Sassanid caravanserai has a two-story main building. Examples of Seljuk caravanserais (Sangi Parand and Mohammadabad Kaj) have a two-story entrance. Some Safavid and Qajar caravanserais have a two-story entrance.

Discussion

Major trade and pilgrimage routes, such as the Silk Road and Atabat routes, shaped architectural similarities among caravanserais built along these paths. Based on available facilities, caravanserais are classified as simple, intermediate, or complex (combined). Complex examples often included secondary elements such as royal residences, mosques, bathhouses, bazaars, water tanks, and ponds.

Geographical and historical contexts played an important role in design variations. For instance, caravanserais in Isfahan province, the capital during the Seljuk and Safavid periods, were more elaborate and included multiple secondary spaces, reflecting the city's political and economic prominence. Royal caravanserais like Jolegir, Madar Shah Morchekhord, Sheikh Ali Khan, Neistanka, Mahyar, Robat Sultan, and Robat Turk were specifically designed for elite travelers and state officials.

Despite common features, no two caravanserais are identical. Their main architectural components, the entrance, porch, central courtyard, rooms, veranda, stables (camel huts), and guard towers, appear consistently but vary in form and arrangement across historical periods. Secondary spaces, such as prayer halls, royal quarters, ponds, and courtyard platforms, were optional additions depending on location, function, and patronage.

The study shows that architectural evolution in caravanserais was gradual, influenced by factors like climate, local building traditions, available materials, and the skill of architects. Physical characteristics such as geometry, symmetry, spatial organization, and overall plan composition were examined in detail. These features demonstrate that Iranian caravanserai architecture follows a structured, rule-based system rooted in earlier construction traditions while adapting to contemporary needs.

Furthermore, architectural similarities among caravanserais built in close historical periods or along the same routes, such as the octagonal caravanserais of Amin Abad, Khan Khoreh, and Deh Bid, and the Chah Qadeh and Gaz caravanserais, suggest the involvement of common architects or patrons.

Recognizing these shared design features not only highlights the systematic and codified nature of Iranian caravanserai architecture but also provides valuable guidance for restoration and preservation efforts. Given the study's wide range of samples spanning diverse historical periods, climatic zones, and spatial geographies, its findings can be meaningfully generalized to other caravanserais within similar contexts.

Conclusion

In response to the research question, it should be stated that physical and metaphysical components, such as climatic, cultural, social, economic, religious, technical, and structural factors, have caused various types to form in the overall shape and architectural elements of caravanserais. For example, the climate of the region causes the formation of covered caravanserais, or the presence of only a veranda in the caravanserais, and the absence of rooms is due to the climate of the region. The caravanserais of Wardeh and Pasangan have no rooms and have a veranda. This type of design has emerged due to the hot climate of the region. The formation of the upper room above the entrance door in some caravanserais is due to the economic, cultural, and political importance of that historical route and the caravanserais. Caravanserais that had strategic locations and were in important geographical locations usually offered more facilities. The existence of spaces such as mosques, bathhouses, coffee houses, and markets next to the caravanserais is due to the influence of economic, political, and cultural components on the design of the caravanserais. Among the influential cultural factors, we can mention the use of two courtyards, a public courtyard and a private courtyard, and the separation of private and public space by designing a dedicated space for the royal residence. The use of indigenous materials and architectural elements such as stone and brick and brickwork decorations, plastering, and tiling caused.

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Conflict of Interest

The authors declare no conflicts of interest.

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References

[1]. M.Y. Kiani, V. Klais, List of Iranian caravanserais (vol. I, II). Iranian Cultural Heritage Organization, Tehran, 1994. Available at: https://surl.li/mhwlgi. Accessed on November 2 , 2025.

[2]. M.K. Pirnia, Introduction to Islamic Architecture of Iran. Science and Technology of Iran University Press, Tehran, 1999. Available at: https://library.richt.ir/site/catalogue/14366. Accessed on November 2, 2025.

[3]. M. Kavian, G. Gholami, A Study of the Evolution of the Architecture of Courtyard Caravanserais in Central Iran. Quarterly Journal of Athar, 37 (75), 49-66, 2017. Available at: http://journal.richt.ir/athar/article-717-1-fa.html. Accessed on November 2, 2025.

[4]. B. Vasigh, Z. Amini Farsani, H. Nasseri, Comparative Comparison of the Proportions Governing the Architecture of Courtyard Caravanserais in Central Iran in the Safavid and Qajar Periods. Iranian Restoration and Architecture Quarterly, 27, 65-78, 2022.

[5]. A. Moshabaki, Comparative Comparison of the Architectural Space of Safavid-Era Caravanserai with a Physical Approach. Green Architecture Quarterly, 12, 11-24, 2018.

[6]. R. Khaghani, B. Shanvaz, Caravanserais of Iran. Pazineh Publication, Tehran, 2016.

[7]. J. Neistani, M. Tatari, Study of Architectural Elements of Entrance Spaces: Case Studies of Safavid Caravanserai of Khorasan Razavi. Payam Bastanshenas (Message of the Archaeologist) Quarterly, 20-21, 2014. Available at: https://surl.li/trrqxd. Accessed on November 2, 2025.

[8]. S. Keyvanlou Shahrestanaki, H. Shadi, Rereading the Physical Characteristics of Sabzevar Caravanserai During the Safavid Period. In Proceedings of the National Conference on Sustainable Architecture and Urban Development, Iran, 2013. Available at: https://civilica.com/doc/214396. Accessed on October 18, 2025.

[9]. S.H. Pourmohammad, Studying the Cognitive Impact of Different Causes and Factors in the Formation and Organization of Iranian Caravanserai. In Proceedings of the National Conference on Humanistic Architecture and Urban Planning. Islamic Azad University of Qazvin, Qazvin, 2013. Available at: https://sid.ir/paper/894186/fa. Accessed on October 24, 2025.

[10]. M. Siroux, Iranian Caravanserai and Small Buildings Between the Roads (I. Behnam, Trans.). Publication of the National Organization for the Preservation of Antiquities of Iran, Tehran, 1949. Available at: https://surl.li/ccqoee. Accessed on November 2, 2025.

[11]. M. Siroux, Ancient Roads of Isfahan Region and their Associated Buildings (M. Mashaikhi, Trans.). Publication of the National Organization for the Preservation of Antiquities of Iran, Tehran, 1978. Available at: https://surl.li/azyvms. Accessed on November 2, 2025.

[12]. T. Khosravi Javid, S.H. Nasakhian, H.R. Jeyhani, Physical-Spatial Typology of Suburban Caravanserais on the Historical Road Network from Isfahan to Rey and Saveh Based on the Spatial Composition of the Architectural Plan. Naqsh-e Jahan (Motif of the World) Quarterly, 15 (1), 49-84, 2025. Available at: https://surl.lu/wuhfbj. Accessed on October 30, 2025.

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ON THE GEOMETRIC ASPECTS OF ARCHITECTURAL COMPOSITIONS

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Abstract: *We consider different aspects of the application of non-Euclidean geometries in architectural compositions. The main attention is put on Lobachevski's and Mandelbrot's fractal geometry. Lobachevski's geometry is indirectly applied to architecture through models such as the Poincaré disc model. Using them, architects can design complex non-Euclidean forms that are represented as concave or saddle-shaped in modern buildings. The ideas of fractal geometry have been increasingly used in architectural compositions since the last decade of the 20th century. It has been noted that if the fractal component of an architectural structure is clearly traced, then this structure has strong architectural aesthetics. Many famous architectural compositions were studied on the subject of the application of non-Euclidean geometry and the level of their fractality. However, these questions have not been considered for Armenian architecture. The current paper is devoted to filling this gap and to drawing the attention of contemporary architects to the subject.*

Keywords: *non-Euclidean geometry, architecture, Poincaré model, fractal, psychology.*

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Geometry is the grammar of architecture, and the world around us is the world of geometry.

Le Corbusier

Introduction

The significant role of geometry in architecture is well known. Classical architectural forms and compositions are largely based on Euclidean geometry, which deals with ideal spatial figures (polyhedra, cylinders, cones, spheres, etc.). Over time, the development of geometry was enriched by new achievements, among which Lobachevski's geometry and Mandelbrot's fractal geometry stood out for their practical applications. These new geometries naturally influenced architectural design, leading to the creation of new, unconventional forms and compositions.

This paper presents geometric essays outlining elements of well-known geometric theories (Lobachevski's non-Euclidean geometry and Mandelbrot's fractal geometry). We consider different aspects of the application of non-Euclidean geometries in architecture. These aspects are illustrated by examples of Armenian (medieval and contemporary) architectural compositions. The paper compiles the series of the previous works [1-3].

The first part of the paper is devoted to Lobachevski's geometry and is predominantly theoretical in nature, including a small number of examples from Armenian and global architecture. During the presentation, solutions are provided for some of Lobachevski's geometric problems that have practical applications.

The second part of the paper is devoted to the practical applications of fractal geometry in architecture. We present the primary method for calculating the fractal dimension of an object—the box-counting dimension method. A fractal analysis is conducted on several famous medieval Armenian structures and contemporary buildings in Yerevan. Objective (quantitative) evaluations of their aesthetic appeal are obtained, demonstrating a high level of aesthetic appeal, which is consistent with known subjective evaluations.

Materials and Methods

In the first part of the work, we consider elements of Lobachevski's non-Euclidean geometry and two of its interpretations (models), the Poincaré model in a half-plane and the Poincaré model in a disc.

The second part is dedicated to fractal geometry. When conducting fractal analysis, various computing tools are used. In this work, the analysis is carried out on the basis of the FrakOut! package, which is very convenient for calculating the fractal parameters of buildings. When evaluating the architectural compatibility of the plan and facade of the temples under consideration, the STATISTICA software package was used to find statistical estimates based on the available data.

Results and Discussion

Euclidean interpretations of non-Euclidean geometry. Poincaré model

Contemporary architecture, especially buildings that utilize unconventional design approaches, has always been attractive. Such structures often employ spatial forms inherent to non-Euclidean geometry. From this perspective, certain knowledge of this area of mathematics will be very useful to architects.

In this section, we will provide some elements of non-Euclidean geometry, including the history of its development and solutions to common problems. As for the use of non-Euclidean geometry in Armenian architecture, there are few of them, but they exist.

Fifth postulate (parallel axiom) of the Euclidean geometry

Among the axioms of Euclid, the fifth postulate stands alone. While all other postulates are intuitively obvious, and their formulations are simple, concise, and understandable, the fifth postulate does not have these advantages. Its phrasing is cumbersome, and it takes an effort to understand its meaning: "If a line segment intersects two straight lines, forming two interior angles on the same side that are less than two right angles, then the two lines, if extended indefinitely, meet on that side on which the angles sum to less than two right angles".

But the difference between the fifth postulate and the others is not limited to this. The fact is that the requirement contained in it refers to the property of a straight line along its entire length. The fifth postulate states that two straight lines are parallel if they do not have a common point, no matter how far they continue. It follows from this that, unlike the other four postulates of Euclid, the fifth postulate cannot be verified in practice.

Naturally, many geometers of those times had a desire to prove the fifth postulate based on the other four. Among them, we note such well-known thinkers as Ptolemy (author of the geocentric system of the world) and Proclus (who wrote the treatise "Comments on Book I of Euclid's Elements"). For example, Proclus found a much simpler equivalent formulation of the fifth postulate (Proclus's axiom): only one straight line parallel to the given one passes through a point outside a straight line.

Apparently, Euclid himself understood that the fifth postulate is special because the proofs of the first 28 theorems of his first book are based only on the first four axioms. The set of those geometric results that follow from the first four axioms of Euclid is called absolute geometry.

In modern times, many attempts to prove the fifth postulate were carried out by the method of contradiction. It is curious to note that in 1763, G.S. Kluge collected and studied about 30 "proofs" of the validity of the fifth postulate and revealed the errors contained in them. From that, he concluded that the fifth postulate is correct and is an independent axiom. Of course, Kluge's conclusion that the fifth postulate is an independent axiom cannot be considered incontestable since, as we know, indirect arguments in favor of any statement cannot be considered as proof of its correctness.

Non-Euclidean geometry of Lobachevski

The problem of the fifth postulate of Euclid, which occupied geometers for more than two millennia, was solved practically simultaneously and independently by German mathematician and physicist C.F. Gauss, Hungarian mathematician J. Bolyai, and Russian scientist N.I. Lobachevski. Their solution boils down to the fact that the fifth postulate cannot be proved based on other postulates of Euclidean geometry. The new geometry was named Lobachevski's geometry because he was the first who did not hesitate to publicly announce results that were at odds with those that had been accepted for over two thousand years.

Non-Euclidean geometry is a set of statements and theorems that can be obtained based on the system of Euclid's axioms if, instead of the parallel axiom, we accept the opposite statement: on a plane through a point that does not belong to a given straight line, more than one straight line can be drawn that does not intersect with this straight line.

Here are some of the differences between non-Euclidean geometry and Euclidean geometry. In Lobachevski's geometry:

1. There are no similar but unequal triangles. It follows that triangles are equal if their angles are equal. If so, then there is an absolute unit of length, i.e., a segment marked by its properties is similar to a right angle specified by its properties. Such a segment can be, for example, the side of a regular triangle with a given sum of angles.
2. The sum of the angles of any triangle is less than π and can be arbitrarily close to zero.
3. Through a point A, not lying on a given straight line a, there are infinitely many straight lines that do not intersect the straight line a and are in the same plane. There are two extreme ones among them, which are called parallel to the straight line a in the sense of Lobachevski.
4. If the lines have a common perpendicular, then they diverge infinitely on either side of it.
5. The circumference is not proportional to the radius but grows faster.

It should be noted that the smaller the area in space (on the Lobachevski plane), the less the geometric relations in this area differ from those of Euclidean geometry. For example, the smaller the triangle, the less the sum of its angles differs from π; and the smaller the circle, the less the ratio of its length to the radius differs from 2π. A decrease in the area is formally equivalent to an increase in a unit of length. Therefore, with a formal increase in the unit of length, the Lobachevski geometry formulas are transformed into the Euclidean geometry formulas.

The denial of the fifth postulate did not lead to a contradiction with the other four axioms and made it possible to create meaningful and logically harmonious geometry. However, the absence of contradictions does not mean that they cannot appear in the future. Naturally, the problem of consistency of the new, non-Euclidean geometry of Lobachevski arises. To prove the consistency of Lobachevski's geometry, it is necessary to show that it is as consistent as Euclid's geometry, which consistency has not been in doubt for centuries. Such proof was given later when interpretations (models) of non-Euclidean geometry were indicated.

E. Beltrami was the first one who constructed an example of a model called a "pseudo-sphere" (Fig.1) in which the first four postulates hold but not the fifth one. From this, it can be seen that non-Euclidean geometry is just as consistent as Euclidean geometry.

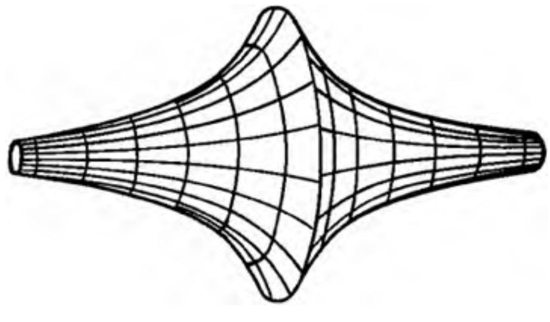


Fig. 1. *Pseudo-sphere of Beltrami*

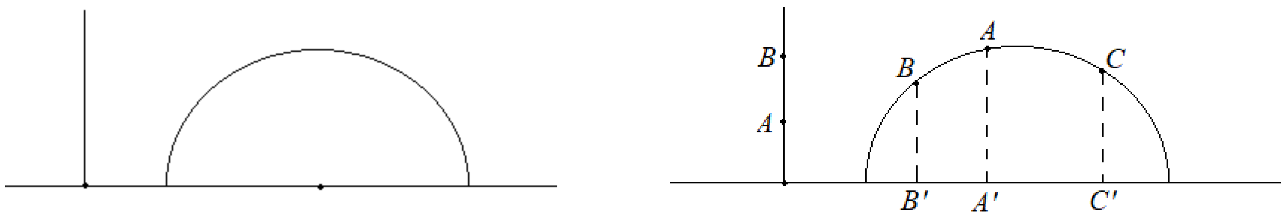
Further, A. Poincaré suggested two models (in a half-plane and in a disc) in which the whole of Lobachevski's geometry is presented. Below, we describe Poincaré models (we refer to [4-7] for details) and bring some examples of solutions to related problems.

Poincaré model in a half-plane

It turns out that the geometry of Lobachevski is not as clear as the geometry of Euclid. Here, the corresponding models come to the rescue, allowing, based on Euclid's planimetry, the creation of a meaningful geometric structure in which the axioms of Lobachevski's geometry are fulfilled. Below, we present one of them, due to H. Poincaré.

In Lobachevski's planimetry, as in Euclidean, the basic concepts are "point", "straight line", the order relation "lie between" for points of a straight line, and "distance between points". All other objects are defined through the above four concepts. The construction of the model begins with the fact that the basic concepts are determined through some notions of Euclidean planimetry, which, in turn, allows defining all other objects in the geometry of Lobachevski. If, in this case, Lobachevski's axioms turn out to be true (verification is carried out using the results of Euclidean geometry), then it is said that the model has been built (implemented). The possibility of constructing such a model testifies to the fact that Lobachevski's geometry is as consistent as Euclidean geometry.

The Poincaré model is constructed as follows. A horizontal line is drawn on the Euclidean plane, which divides the plane into two half-planes. This line is called the absolute. Points in the Lobachevski planimetry are the points in the upper half-plane that do not lie on the absolute. Any semicircle centered on the absolute or a ray perpendicular to the absolute, the origin of which lies on the absolute, is called a straight line (Fig. 2a).



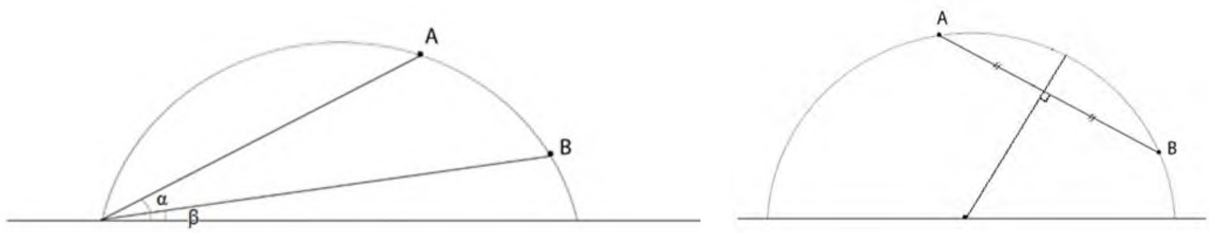
a. **b.**

Fig. 2. *Straight lines and points in the Poincaré model*

Point *A* lies between two other points, *B* and *C,* on the Lobachevski line if its projection onto the absolute lies between the projections of points *B* and *C* (Fig. 2b). The distance $d(A,B)$ between points *A* and *B* is determined by the straight line connecting *A* with *B*. It can be found in the following way. For the points *A* and *B*, let the angles α and β be specified as shown in Fig. 3a. Then

$$d(A,B) = c\left|\ln\frac{|\operatorname{tg}\alpha|}{|\operatorname{tg}\beta|}\right|,$$

where *c* is some positive constant.

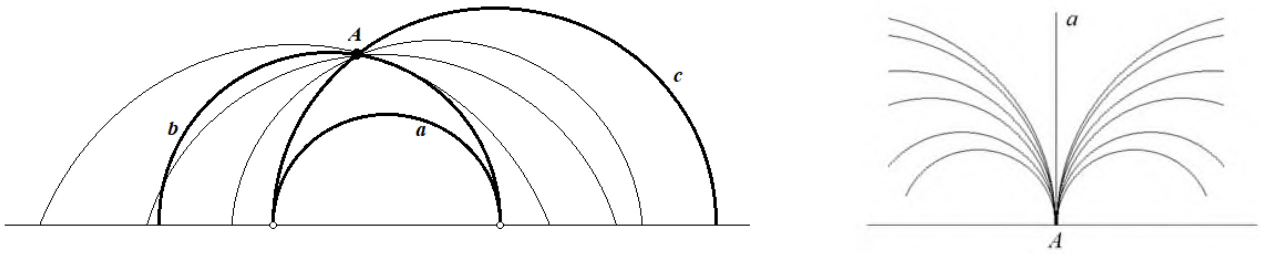


a. **b.**

Fig. 3. a. *Angles α and β in the formula for the distance d(A,B);*
b. *Construction of a semicircle containing two given points A and B*

Let us show that in the constructed model, all the axioms of Lobachevski's geometry are fulfilled. To check the first axiom, it is sufficient to construct a semicircle containing the given two points, *A* and *B,* within the framework of Euclidean geometry. This construction is carried out as follows. Let us connect points *A* and *B* with a segment, understood in the sense of Euclidean geometry, and from its center, we lower the perpendicular to the absolute. The point of intersection of this perpendicular with the absolute will be the center of the required semicircle (Fig. 3b).

The fulfillment of axioms 2, 3, and 4 is obvious. Let us turn to the consideration of the fifth axiom. It is easy to see that an infinite set of straight lines that do not intersect with a pass through any point A that does not lie on the Lobachevski line a (Fig. 4a). Among these lines, those that have one point in common with a on the absolute (lines b and c in Fig. 4a) stand out. Such Lobachevski lines are called parallel to a. We see that two straight lines are passing through point A and parallel to a. In Fig. 4b, one can see a pencil of lines parallel to line a, which is perpendicular to the absolute, and passing through a point A at infinity lying on the absolute.



a. **b.**

Fig. 4. **a.** *Lines b and c passing through point A and parallel to a;*
b. *Pencil of lines parallel to the line a*

Figure 5 shows triangles of Lobachevski geometry. It can be seen from this drawing that the sum of their angles is less than π. Note also that the bigger the triangle, the more its sum of angles differs from π. To see it, compare triangles ABC and ADE, as well as triangles ABC and AGF.

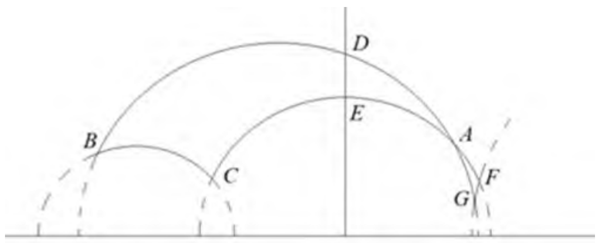


Fig. 5. *Triangles of Lobachevski geometry*

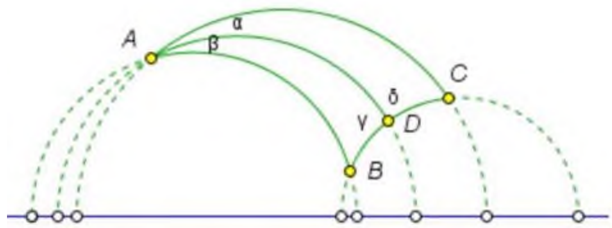


Fig. 6. *Triangles ABD and ACD*

When solving problems of Lobachevski planimetry (in the Poincaré model), the conditions of the problem are translated into the language of Euclidean geometry, after which the problem is solved by its methods. Let us give some examples.

Problem. Show that triangles in the Lobachevski plane can have different sums of angles.

Solution. Consider the triangles ABD and ACD shown in Figure 6. Let us calculate the sums σ_{ABD} and σ_{ACD} of their angles. We have

$$\sigma_{ABD} + \sigma_{ACD} = (\beta + \gamma + \angle B) + (\alpha + \delta + \angle C).$$

Using the facts that $\alpha + \beta = \angle A$ and $\gamma + \delta = \pi$, further we can write

$$\sigma_{ABD} + \sigma_{ACD} = \angle A + \angle B + \angle C + \pi = \sigma_{ABC} + \pi.$$

Hence, one of the sums, σ_{ABD} or σ_{ACD}, is less than π. Suppose, $\sigma_{ACD} < \pi$. Then from the equality

$$\sigma_{ABD} + (\sigma_{ACD} - \pi) = \sigma_{ABC},$$

it follows that $\sigma_{ABD} > \sigma_{ABC}$. Thus, we have found two triangles, ABD and ABC with different sums of its angles.

Problem. Let A, B, and C be points in the Lobachevski plane, not lying on one straight line, and let the straight line a not pass through any of these points. Prove that if the straight line a passes through the point of the segment AB, then it passes through the point of the segment AC or BC.

Solution. In Euclidean geometry, the following statement is true: Two circles intersect if and only if one of them passes through the inner point of the other circle. Let the line *a* (in the sense of Lobachevski) intersect the segment *AB* (Fig. 7). Then either point *A* will be internal for the Euclidean circle *a*, or that will be point *B*. Suppose that this is point *B*. Then, if point *C* is an internal point for the Euclidean circle *a*, the line *a* intersects the segment *AC*. Otherwise, *a* intersects the segment *BC*.

Further, we will prove the analogue of the Pythagorean theorem in Lobachevski's geometry.

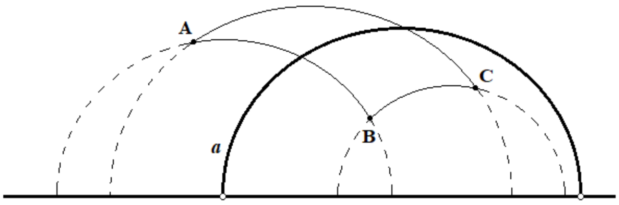


Fig. 7. *Line a intersecting segment AB*

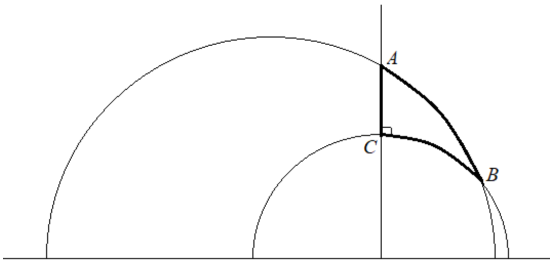


Fig. 8. *Right triangle ABC*

Theorem. *For any right triangle, the following equality holds:*

$$\mathrm{ch}c = \mathrm{ch}a \cdot \mathrm{ch}b,$$

where c represents the length of the hypotenuse and a and b the lengths of the triangle's other two sides.

Proof. Consider the right triangle *ABC* with the right angle *C* (Fig. 8). Without loss of generality, we will assume that the vertices *A*, *B,* and *C* of this right triangle correspond to complex numbers *ri*, *u* + *v*i and *I*, respectively, where *r* > 1 and $u^2 + v^2 = 1$, since this can always be achieved with some non-Euclidean motion. Then we have

$$\mathrm{ch}a = \mathrm{ch}|AC| = \mathrm{ch}d(A, C) = 1 + \frac{|ri - i|^2}{2r} = \frac{1 + r^2}{2r},$$

$$\mathrm{ch}b = \mathrm{ch}|BC| = \mathrm{ch}d(B, C) = 1 + \frac{|u + vi - i|^2}{2v} = \frac{1 + u^2 + v^2}{2v} = \frac{1}{v},$$

$$\mathrm{ch}c = \mathrm{ch}|AB| = \mathrm{ch}d(A, B) = 1 + \frac{|ri - u - vi|^2}{2rv} = \frac{u^2 + v^2 + r^2}{2rv} = \frac{1 + r^2}{2rv}.$$

Hence,

$$\mathrm{ch}a \cdot \mathrm{ch}b = \frac{1 + r^2}{2r} \cdot \frac{1}{v} = \frac{1 + r^2}{2rv} = \mathrm{ch}c.$$

Lobachevski noticed that the non-Euclidean geometry he created in an infinitesimal, that is, in the first approximation, coincides with the geometry of the Euclidean plane. Let us illustrate this with the example of the Pythagorean theorem. Using the series expansion of the hyperbolic cosine

$$\mathrm{ch}z = 1 + \frac{z^2}{2!} + \frac{z^4}{4!} + \frac{z^6}{6!} + \cdots,$$

we obtain for the Pythagorean theorem the following relation:

$$1 + \frac{c^2}{2!} + \frac{c^4}{4!} + \cdots = \left(1 + \frac{a^2}{2!} + \frac{a^4}{4!} + \cdots\right)\left(1 + \frac{b^2}{2!} + \frac{b^4}{4!} + \cdots\right).$$

Keeping the lower order terms, we arrive at the Pythagorean theorem of Euclidean geometry:

$$c^2 = a^2 + b^2.$$

Poincaré disc model

In addition to the above model, Poincaré proposed the model of the Lobachevski plane in a disc. This model is described as follows. The plane itself is represented as the inner part of the circle of radius 1 with the center at the origin of the complex plane, that is,

$$\mathcal{B} = \{z \in \mathbb{C}: |z| < 1\}.$$

The points of the circumference bounding the disc do not belong to the plane, and the circumference itself is called the absolute.

This model can be obtained from Poincaré's model in a half-plane through the following transformation:

$$w = \frac{z - i}{z + i}.$$

Indeed,

$$|w| = \left|\frac{x + i(y - 1)}{x + i(y + 1)}\right| = \sqrt{\frac{x^2 + (y - 1)^2}{x^2 + (y + 1)^2}} \leq 1.$$

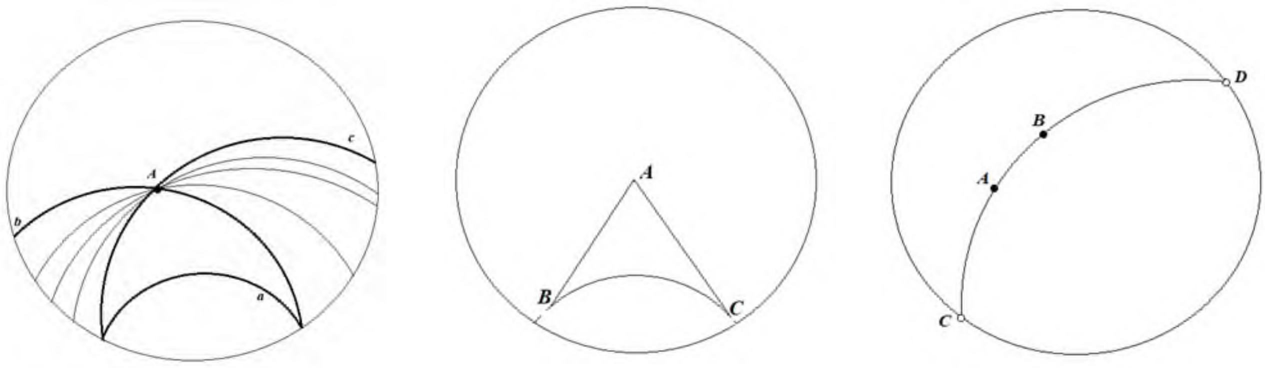
The inverse transition is obviously carried out by means of the mapping:

$$w = i\frac{1 + z}{1 - z}.$$

The lines in this model are the arcs of the circles perpendicular to the absolute. Recall that two curves are called perpendicular if their tangents at the point of intersection of the curves are mutually perpendicular. The lines forming a diameter of the absolute are called special.

It is quite obvious (Fig. 9a) that in the defined model, if a straight line *a* and a point *A* not belonging to it are given, then through the point *A* it is possible to draw an arbitrarily large number of straight lines that do not intersect the straight line *a*. From Fig. 9a it can be seen that among such lines, two stand out – line *b* and line *c*. They are characterized by the fact that they have a common point with line *a* on the absolute. It is these two straight lines in the Poincaré model that are called parallel to the straight line *a*. All others passing through point *A* and having no common points with it are inside the angle formed by straight lines *b* and *c*. Such straight lines are called diverging.

It follows from what has been said that in Lobachevski's geometry, parallel lines do not possess the property of transitivity, i.e., from the fact that, for example, line *b* is parallel to line *a*, and line *a* is parallel to line *c*, it does not follow that line *b* is parallel to line *c* (Fig. 9a). However, this fact takes place in Euclidean geometry.



a. **b.** **c.**

Fig. 9. *Poincaré disc model:* **a.** *lines drawn through point A and parallel to a;* **b.** *triangle;* **c.** *distance*

The choice of one or the other model depends on the task. In particular, the fact that the sum of the angles of a triangle in Lobachevski's geometry is less than π is much easier to see on a disc model (Fig. 9b).

Let us show how the distance between points is determined in this Poincaré model of Lobachevski's plane. Let points A and B be given, and let the straight line (in the sense of Lobachevski) connecting these points intersect the absolute at points C and D (Fig. 9c). Then the distance $d(A,B)$ between points A and B is determined as follows:

$$d(A,B) = \left|\ln\frac{CB/CA}{BD/AD}\right|,$$

where CB, CA, BD, and BA are the lengths of the corresponding arcs in the sense of Euclid.

Problem. Let points A and B lie on the same singular line in the Poincaré disc model, and let their Euclidean distances to the center of the disc be known. Calculate the distance from A to B in the sense of Lobachevski's geometry.

Solution. Without loss of generality, let us assume that points A and B belong to the diameter lying on the OY axes of the complex plane.

Let the Euclidean distances to the center from points A and B be equal to α and β, respectively, $0 \le \alpha < \beta < 1$. Then to point A, it corresponds to the complex number $i\alpha$, and to point B, it corresponds to the number $i\beta$. Thus, we can write

$$d(A,B) = d(i\alpha, i\beta) = 2\text{arth}\left|\frac{i\alpha - i\beta}{1 - i\alpha\overline{(\imath\beta)}}\right| = 2\text{arth}\left|\frac{\alpha-\beta}{1-\alpha\beta}\right| = ln\left(\frac{1+\left|\frac{\alpha-\beta}{1-\alpha\beta}\right|}{1-\left|\frac{\alpha-\beta}{1-\alpha\beta}\right|}\right) =$$

$$= ln\frac{(1+\beta)(1-\alpha)}{(1-\beta)(1+\alpha)} = ln\frac{1-\alpha}{1-\beta} + ln\frac{1+\beta}{1+\alpha} = ln\left(1+\frac{\beta-\alpha}{1-\beta}\right) + ln\frac{1+\beta}{1+\alpha}.$$

Elements of Lobachevski geometry in architecture

Lobachevski's geometry is applied indirectly to architecture through models, such as the pseudo-sphere model or the Poincaré model in a disc. Using these models, architects can design complex non-Euclidean forms, which in modern buildings are represented as concave or saddle-shaped.

Lobachevski's geometry inspired many architectures of a new time as well. Its advances allowed the development of new, original design methods for the new architecture. Among the architects of modern times, we will name Ernst Neufert, Zaha Hadid, Frank Gehry, and the great architect Antoni Gaudi. Examples of buildings constructed with the usage of non-Euclidean geometry include Casa Batllo, built in 1900 by famous architect Antonio Gaudi in the Art Nouveau style, where the main idea is to mimic forms that are found in nature, which gives the building a unique look; the Cleveland Clinic Center for Medical Art and Photography, built by Frank Gehry in the postmodern style; and Shell House, built in 2008 by Japanese architecture studio ARTechnic architects (Fig.10).

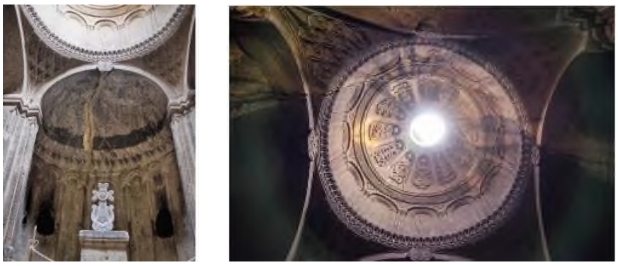
Triangles of Lobachevski geometry, called sails, are also widely used. For example, they are used in architecture to construct domes. These triangles are used to solve the problem of how to put a dome with a round base on a square structure.

One can find a lot of examples of the mentioned construction in Armenian churches. Fig. 11a shows Haghpat Monastery, which is a medieval monastery complex in Haghpat, Armenia, built between the 10th and 13th centuries. On the right-hand side of Fig. 11a, triangles of Lobachevski geometry are clearly viewed, which are used to support the dome. It should be noted that apart from one or two minor restorations carried out in the eleventh and twelfth centuries, the church has retained its original character. The monastery has been damaged many times. Sometime around 1130, an earthquake destroyed parts of Haghpat Monastery, and it was not restored until fifty years later. It also suffered numerous attacks by armed forces in the many centuries of its existence and from a major earthquake in 1988. Nevertheless, much of the complex is still intact and stands today without substantial alterations.

b. *Cleveland Clinical Center for Medical Art and Photography*

a. *Casa Batllo* **c.** *Shell House*

Fig. 10. *Architecture inspired by Lobachevski's geometry*



a. **b.**

Fig. 11. *Sails in Armenian architecture:* **a.** *Haghpat monastery;* **b.** *Geghard Church*

Another example (Fig. 11b) is the dome in the Geghard church. This is a medieval monastery in the Kotayk province of Armenia, being partially carved out of the adjacent mountain. Here, the sails are used not only as a part of construction but also as a decoration.

Fractal geometry and quantitative evaluation of the aesthetic appeal of architecture compositions

The basic figures of classical (Euclidean) geometry are simple and clear: circle, sphere, cylinder, pyramid, etc. Their surfaces are assumed to be ideal, both in terms of their shapes and in terms of their surface properties. Given such limitations, classical geometry can only describe a very narrow class of natural structures and phenomena, but not complex physical objects, such as the shapes of clouds and mountains, tree crowns, or the human bronchial system.

Geometry describing non-standard forms was proposed by B. Mandelbrot [8] based on the concept of fractal introduced by him. It was called fractal geometry. In contrast to classical Euclidean geometry, where objects are idealized (their surfaces are assumed to be perfectly smooth, without any irregularities, cracks, or breaks), fractal geometry studies the patterns inherent in natural objects, processes, and phenomena with the presence of roughness, brokenness, and other complexities [9-11]. It offers a variety of ways to describe and measure both natural and man-made objects.

Fractals and fractal geometry

According to Mandelbrot [8], a fractal is a structure consisting of parts that are in some sense similar to the whole (or to each other). From a mathematical point of view, a fractal is a geometric figure (a set of points in Euclidean space) whose fractal dimension (the Hausdorff-Besicovitch dimension) is either fractional or exceeds its topological dimension.

The fractal dimension for a finite set G in $\mathbb{R}^n$ is defined as follows. Let $\mathbb{Z}^n(\Delta)$ be a cubic lattice in $\mathbb{R}^n$ with cube (cell) edge length equal to Δ. Let $N(\Delta)$ be the minimum number of lattice cubes needed to cover G. Then, the fractal dimension D of G is defined by

$$D = -\lim_{\Delta \to 0} \frac{\ln N(\Delta)}{\ln \Delta}.$$

This dimension can be defined equivalently based on the following requirement:

$$\lim_{\Delta \to 0} N(\Delta)\Delta^d = \begin{cases} 0 & \text{if } d > D, \\ \infty & \text{if } d < D. \end{cases}$$

Thus, the dimension D of the set G is essentially the boundary that shows that if $d < D$, then the number of cubes $N(\Delta)$ is insufficient to cover the set G, and if $d > D$, then the number of cubes is excessive for coverage.

It is generally accepted that the fractal dimension is a characteristic property of fractals, i.e., if the dimension D is not an integer, then the set G is considered a fractal. The Hausdorff-Besicovitch dimension increases with the degree of tortuosity of the object. For a straight line, it is equal to one; for a slightly tortuous line, it is 1.03; for a more tortuous line, it is 1.16; and for a strongly tortuous line, it is 1.57, and so on.

In addition to natural fractals (such as island coastlines, snowflakes, crystals, and heads of broccoli), there are also artificial (non-natural) fractals. The first examples of non-natural fractals were constructed at the end of the nineteenth century in connection with purely mathematical problems of function theory. From the point of view of classical mathematical analysis, they had extremely unusual properties. For example, this is the Cantor set (Cantor dust), the nowhere differentiable Weierstrass function, the Koch snowflake, the Brownian curve on the plane, etc. For some of them, fractal dimensions have been calculated: the Cantor set has a fractal dimension $D = \ln 2 / \ln 3$, and for a Brownian curve on a plane, it is equal to 2, that is, exceeds its topological dimension.

Practical methods for calculating the fractal dimension play an important role. One of the most popular methods is the method of counting cells that have a non-empty intersection with the image being studied (box-counting dimension method). Apparently, W. Lorenz [12] and C. Bovill [13] were the first to study and use this method most fully. Let us describe in general terms the algorithm for applying this method.

In the first step, a cubic (square) grid with the cell edge length (scale) equal to Δ is superimposed on the image under study. Initially, Δ is taken to be equal to L, where L is the length of the rectangle containing all the images. Let $N(\Delta)$ be the number of all cubes that have a non-empty intersection with the image under study. Next, the ratio $-\log \mathrm{N}(\Delta) / \log \Delta$ is considered, and its behavior is investigated under stepwise changes in the scale Δ.

The scale is reduced by half at each step. The process can continue indefinitely, but in practical applications, it is stopped depending on the requirements of the task. The slope of the graph of $\log \mathrm{N}(\Delta)$ from $-\log \Delta$ gives an approximate value of the fractal dimensions of the image.

Fractals in architecture

In architecture, fractal principles are used in the design of objects using computer modeling. These principles can be used to create unique and very interesting architectural forms [11].

Another application of fractal geometry in architecture came from psychology where objective (quantitative) methods of the aesthetic appeal evaluation of architectural compositions were developed. The first studies in the psychology of fractal perception were conducted by J. Sprott's group [14]. Similar studies were conducted by R. Taylor [15], who demonstrated that the overwhelming majority of experimental participants preferred fractal patterns. Sprott found that the attractiveness of fractal objects correlates with their fractal dimension. The results of experiments showed that participants preferred objects with a fractal dimension between 1.1 and 1.5.

Research on the psychology of fractal perception is currently underway [16-20]. These studies have confirmed the hypothesis that the aesthetic appeal of architectural compositions is largely determined by the value of their fractal dimension.

There are many monuments of world architecture for which fractal analysis has been carried out. These are remarkable Gothic cathedrals in Europe, beautiful mosques of Islamic architecture, and unique Hindu temples [21-24].

Regarding Armenian architecture, publications on the fractal analysis of its compositions are nearly absent. In recently published works [2-3], the author conducted a fractal analysis of three major monuments of medieval Armenia (the Hripsime temple, the Zvartnots Cathedral, and the Cathedral of the Holy Virgin in Ani) as well as some modern compositions (the Yerevan Cascade, the Government House #2 on the Republic Square, the Cathedral of Saint Gregory the Illuminator, and the Church of the Holy Trinity). In this section, we briefly present the obtained results.

Fractal analysis of medieval Armenian temples

In [2], a fractal analysis of the temples of Hripsime and Zvartnots, as well as the Ani Cathedral, was presented. A statistical analysis of the compatibility of the plan and facade of these buildings was also carried out.

The obtained results are summarized in Table 1. They show that the temples under consideration have high architectural attractiveness, and their plan and facade are in excellent agreement with each other.

Table 1. Calculations of the fractal dimension of the facade and plan of Armenian temples

Calculation of fractal dimension between:		Fractal dimension					
		Hripsime		Zvartnoc		Ani cathedral	
large grid size	small grid size	facade	plan	facade	plan	facade	plan
200	100	1.46	1.74	1.64	1.67	1.56	1.48
100	50	1.48	1.58	1.54	1.57	1.53	1.50
50	25	1.49	1.49	1.48	1.49	1.56	1.43
25	12.5	1.49	1.51	1.47	1.43	1.5	1.13
average fractal dimension		1.48	1.58	1.533	1.540	1.537	1.385

Hripsime. The temple was built by Catholicos Komitas in 618 to the east of Echmiadzin on the burial site of Saint Hripsime. It is a central-domed structure with an internal cross-shaped base. It is a recognized masterpiece of Armenian architecture.

The temple of Hripsime has an average fractal dimension of 1.48. The calculations also show that the standard deviation of these data from the average is 0.014. Regarding the architectural plan, the following estimates were obtained: the average fractal dimension is 1.58 with a standard deviation of 0.113. The correlation between the fractal dimensions of the facade and the plan is –0.997.

Zvartnots. The Zvartnots Cathedral was founded by Catholicos Nerses III in the middle of the 7th century, not far from Vagharshapat (Echmiadzin), in the place where, according to legend, Gregory the Illuminator and the king of Armenia, Trdat, met. This majestic temple is a tetraconch (a central-domed structure with a plan in the form of a cross with rounded ends).

The Zvartnots temple has an average fractal dimension of 1.533 with a standard of deviation 0.008 of the obtained data from the average. For the architectural plan, the average fractal dimension is 1.54 with a standard deviation of 0.104. The correlation between the fractal dimensions of the facade and the plan is 0.974.

Cathedral of the Holy Virgin in Ani. The Ani Cathedral is the pinnacle of Armenian architecture of the 9th-11th centuries. It is a prototype of Gothic architecture. Its architectural forms are similar to European Gothic.

Regarding Gothic, we note that there is a very reasonable assumption that the first object where Gothic principles were applied was not the Cathedral of Saint-Denis (a suburb of Paris), but the Cathedral of the Holy Virgin in Ani. The interior of this temple clearly contains such architectural compositions as elongated pointed arches and bunches of columns with ribbed vaults. These compositions were developed in Gothic architecture, which was widespread in Western Europe.

In his major work [25], Professor of the University of Vienna J. Strzygowski writes, "Consequently, it remains to be recognized that the Armenians built in the Gothic style approximately 150 years earlier than was the case in Europe".

The Ani Cathedral has an average fractal dimension of 1.537 with a standard deviation of 0.029. The architectural plan has an average fractal dimension of 1.385 with a standard deviation of 0.172. The correlation between the fractal dimensions of the facade and the plan is 0.797.

Fractal analysis of contemporary Armenian architectural structures

In [3], a fractal analysis for several contemporary Armenian architectural structures with obvious fractal motifs was announced: the Yerevan Cascade, the Government House #2 on the Republic Square, the Cathedral of Saint Gregory the Illuminator, and the Church of the Holy Trinity. The obtained results are summarized in Table 2. Below, we will present the fragments of the process of calculating the fractal dimension for the mentioned constructions.

Table 2. Calculations of the fractal dimension of modern Armenian architectural structures

Calculation of fractal dimension between:		Cascade	Government House #2	Cathedral of St. Gregory the Illuminator	Holy Trinity Church
large grid size	small grid size				
128	64	1.51	1.56	1.66	1.63
64	32	1.49	1.51	1.60	1.63
32	16	1.44	1.52	1.52	1.59
16	8	1.38	1.49	1.46	1.52
average fractal dimension		1.455	1.52	1.56	1.593

Yerevan Cascade. The Yerevan Cascade is an architectural and monumental complex consisting of a multi-level staircase with terraces, fountains, sculptures, and exhibition halls. Its construction began in 1980 but was halted in the late 1980s due to the Spitak earthquake, the collapse of the USSR, and the First Karabakh War. The architecture combines elements of Soviet modernism with traditional motifs of Armenian stone architecture.

Figure 12 shows fragments of the process of calculating the fractal dimension of the Cascade. From the obtained data, it follows that the Cascade has an average fractal dimension of 1.455. The calculations also show that the standard deviation of these data from the average is 0.058.

Government House #2 on the Republic Square. Republic Square is the central square of Yerevan. Government House #2 on this square was built in 1955 according to the design of Samvel Safaryan, Rafael Israelyan, and Varazdat Arevshatyan. From 1996 to 2016, the building belonged to the Ministry of Foreign Affairs of the Republic of Armenia. Figure 13 shows fragments of the process of calculating the fractal dimension for this building. The Government House has an average fractal dimension of 1.52 with a standard deviation of 0.029 of these data from the average.

Cathedral of St. Gregory the Illuminator. The Cathedral of Saint Gregory the Illuminator is the largest cathedral built in Yerevan. It was erected to commemorate the 1700th anniversary of Armenia's adoption of Christianity as the state religion. Construction began in 1997 and took approximately four years. The cathedral's architect is Stepan Kyurkchyan.

The Cathedral of St. Gregory the Illuminator has an average fractal dimension of 1.56 with a standard deviation of 0.088. Figure 14 shows fragments of the process of calculating its fractal dimension.

Church of the Holy Trinity. The Holy Trinity Church was built in 2003 in Yerevan, in the Malatia-Sebastia district. The design was developed by the honored architect Baghdasar Arzumanyan. The church is modeled after the Zvartnots Cathedral.

Figure 15 shows fragments of the process of calculating the fractal dimension of the church. The results show that the Church of the Holy Trinity has an average fractal dimension of 1.593 with a standard deviation of 0.052.

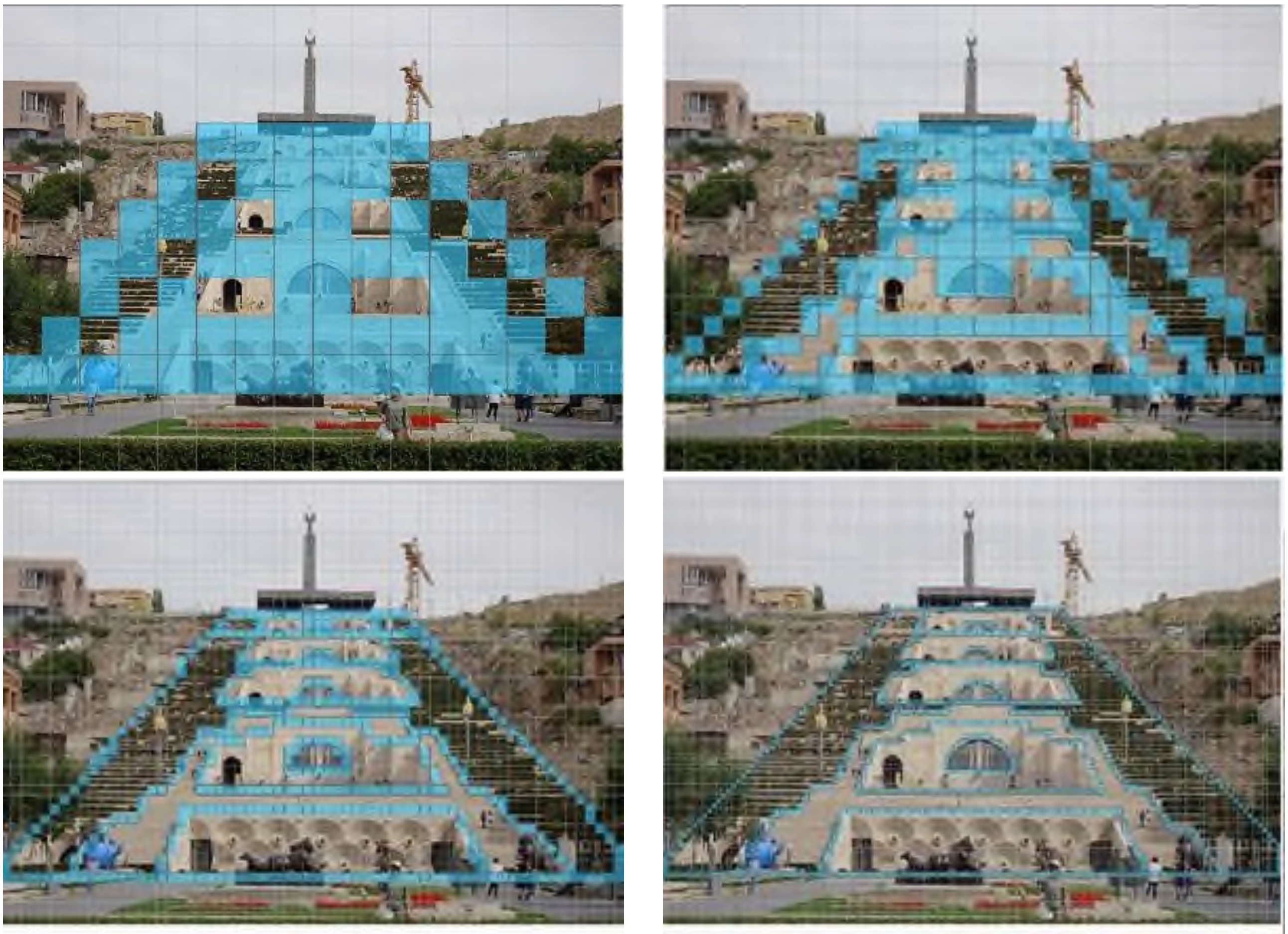


Fig. 12. *Calculation of the fractal dimension of the facade of the Yerevan Cascade*

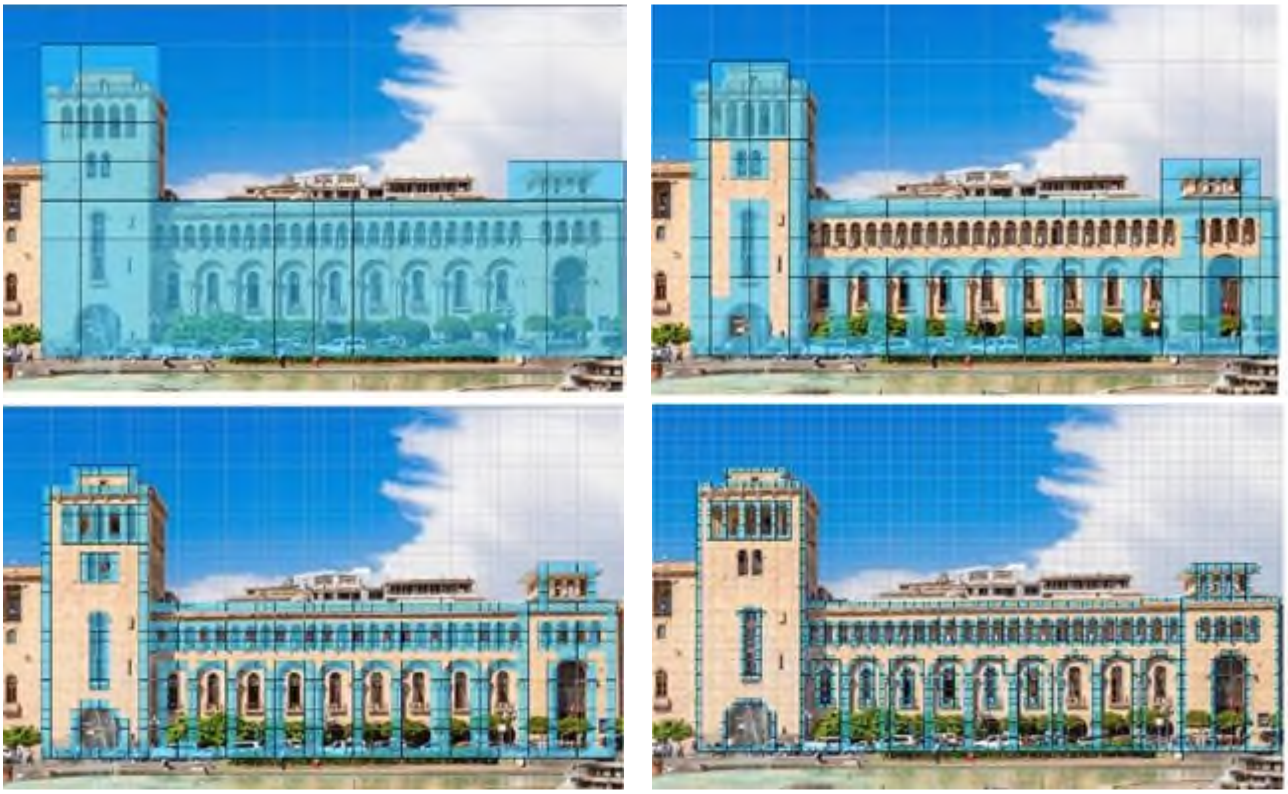


Fig. 13. *Calculation of the fractal dimension of the facade of the Government House #2*

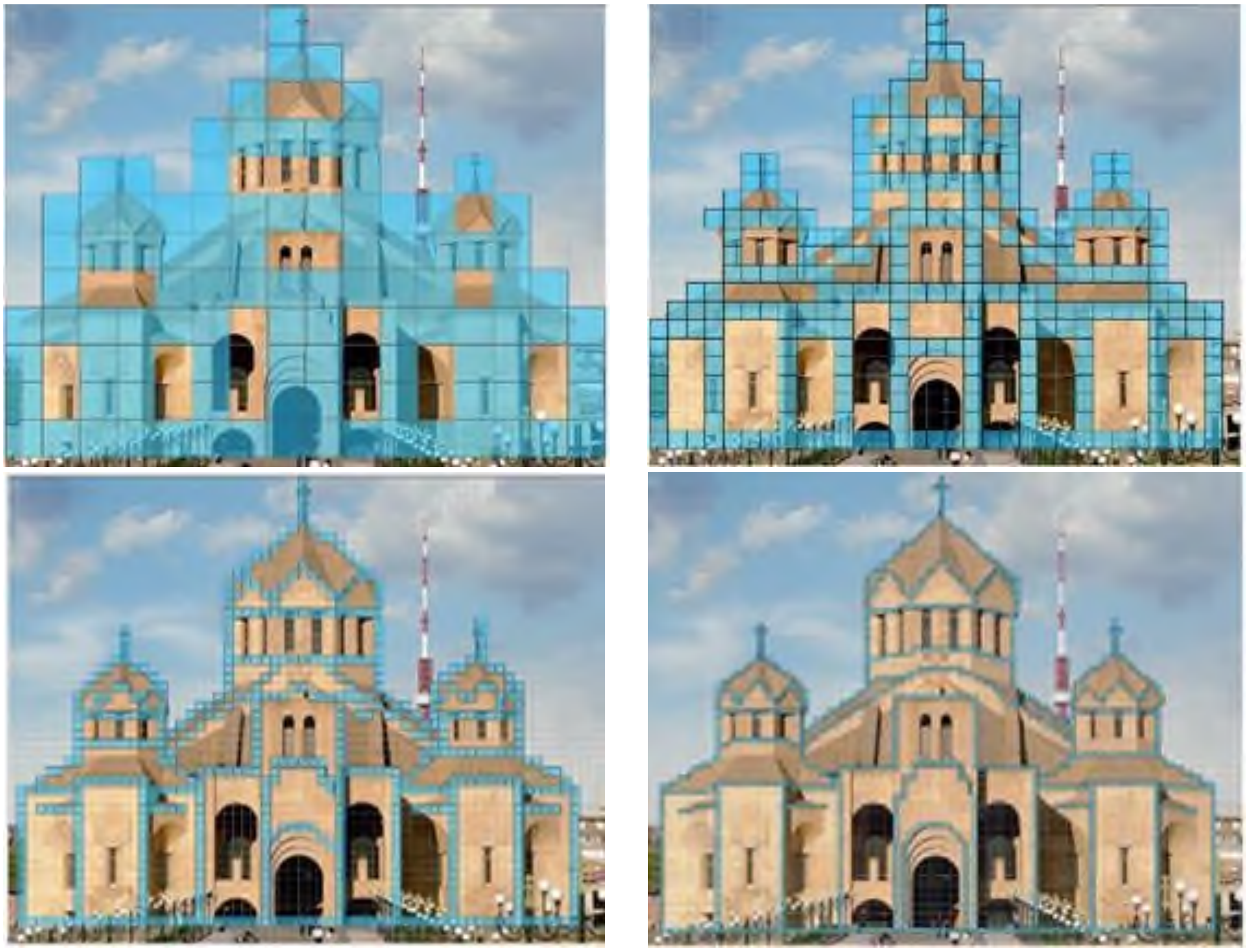


Fig. 14. *Calculation of the fractal dimension of the facade of the St. Gregory the Illuminator cathedral*

Fig. 15. *Calculation of the fractal dimension of the facade of the Holy Trinity Church*

Conclusion

One of the motivations for writing this paper was the desire to draw the attention of Armenian specialists to contemporary trends that are increasingly gaining ground in modern architectural research. This primarily concerns the ideas of Lobachevski geometry and Mandelbrot fractal geometry. Clearly, productive application of the methods of these geometric disciplines requires a certain knowledge of their fundamentals. For this reason, in addition to the results themselves, the paper also presents some insights into the theory of these geometries.

Elements of non-Euclidean geometry are often found in Armenian architectural compositions. For example, triangles of Lobachevski geometry, called sails, are used in architecture to solve the problem of how to put a dome with a round base on a square structure. Such sails can be found in many medieval and modern Armenian churches. In the present paper, we provided some elements of Lobachevski geometry which have applications in architecture.

As for the fractal geometry, research on fractal analysis of Armenian architectural compositions is nearly absent. In the present paper, we briefly described the fractal analysis of three major monuments of medieval Armenia (the Hripsime temple, the Zvartnots Cathedral, and the Cathedral of the Holy Virgin in Ani), conducted by one of the authors in [2], as well as gave a detailed fractal analysis of several contemporary Armenian architectural structures (the Yerevan Cascade, the Government House #2 on the Republic Square, the Cathedral of Saint Gregory the Illuminator, and the Church of the Holy Trinity) announced in [3]. Fractal analysis of the examined Armenian architecture compositions showed a high level of consistency between subjective and objective assessments of their aesthetic appeal.

Conflict of Interest

The authors declare no conflicts of interest.

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References

[1]. A. Nahapetyan, Euclidean Interpretations of Non-Euclidean Geometry. Poincaré Model. "Quantum" College, Yerevan, 2022 (unpublished manuscript).
[2]. A. Nahapetyan, Fractal Geometry and Quantitative Evaluation of the Aesthetic Appeal of Ancient Armenian Architecture Monuments. Mathematical Problems of Computer Science, 63, 2025, 42-53. Doi: https://doi.org/10.51408/1963-0130
[3]. A. Nahapetyan, Elements of Fractal Geometry in Armenian Architectural Compositions. Mathematics (NAS RA), 2025 (in press).
[4]. R. Courant, H. Robbins, What is Mathematics? An Elementary Approach to Ideas and Methods. Oxford University Press, 2nd ed., 1996.
[5]. B.F. Kagan, Osnovy geometrii. Gostekhizdat, 1949 (in Russian).
[6]. D. Marshall, P. Scott, A Brief History of Non-Euclidean Geometry. The Australian Mathematics Teacher, 60 (3), 2004, 2-4.
[7]. V.V. Prasolov, Geometriya Lobachevskogo. MCCME, Moscow, 3rd ed., 2004 (in Russian).
[8]. B.B. Mandelbrot, The Fractal Geometry of Nature. W.H. Freeman and co., San Francisco, 1982.
[9]. R.M. Crownover, Introduction to Fractals and Chaos. Jones and Bartlett Publishers, 1995.
[10]. J. Feder, Fractals. Plenum Press, New York, 1988.
[11]. N.A. Salingaros, Architecture, Patterns, and Mathematics. Nexus Network Journal, 1, 1999, 75-86. Doi: https://doi.org/10.1007/s00004-998-0006-0
[12]. W. E. Lorenz, Fractals and Fractal Architecture: PhD thesis, Vienna University of Technology, 2003.
[13]. C. Bovill, Fractal Geometry in Architecture and Design, Birkhäuser, 1996.
[14]. J.C. Sprott, Strange Attractors: Creating Patterns in Chaos. M&T Books, New York, 1993.
[15]. R.P. Taylor, Reduction of Physiological Stress Using Fractal Art and Architecture. Leonardo, 39 (3), 2006, 245-251.
[16]. S.D. Pyankova, Fraktalno-analiticheskiye issledovaniya v psikhologii: osobennosti vospriyatiya samopodobnykh obyektov. Psychological Studies, 9 (46), 2016 (in Russian). Doi: https://doi.org/10.54359/ps.v9i46.484
[17]. S.D. Pyankova, Subyektivnyye otsenki vizualnoy slozhnosti i esteticheskoy privlekatelnosti fraktalnykh izobrazheniy: individualnyye razlichiya i geneticheskiye vliyaniya. Psikhologicheskiye issledovaniya, 12 (63), 2019 (in Russian). Doi: https://doi.org/10.54359/ps.v12i63.238
[18]. N.A. Salingaros, Fractal Art and Architecture Reduce Physiological Stress. Journal of Biourbanism, 2 (2), 2012, 11-28.
[19]. C.M. Hagerhall, T. Purcell, R. Taylor, Fractal Dimension of Landscape Silhouette Outlines as a Predictor of Landscape Preference. Journal of Environmental Psychology, 24 (2), 2004, 247-255. Doi: https://doi.org/10.1016/j.jenvp.2003.12.004
[20]. F.I. Mavrikidi, Fraktalnaya matematika i priroda peremen. Delphis, 54 (2), 2008 (in Russian).
[21]. P.K. Acharya, An encyclopaedia of Hindu architecture (vol.7). Oxford University Press, London, 1946.

[22]. H.D.A. Ismail, Fractal analysis of masterpieces of Islamic architecture – The Mosque of Ahmad Shah and Taj Mahal: justification of the method and experience of application (in Russian). Architecture and Modern Information Technologies, 4 (21), 2012 (in Russian).
[23]. H.D.A. Ismail, M.Yu. Shishin, Application of a Multi-Stage Fractal Method in Analysis Masterpieces of Islamic Architecture – Ahmad Shah Mosque. Art of Eurasia, 3 (10), 2018, 37-47 (in Ruassin). Doi: https://doi.org/10.25712/ASTU.2518-7767.2018.03.003
[24]. I.A. Mayatskaya, G.I. Fazylzyanova, B M. Yazyev, S.B. Yazyeva, Fraktalnost goticheskoy arkhitektury. Engineering Journal of Don, 4, 2025 (in Ruassin).
[25]. J. Strzygowski, Die Baukunst der Armenier und Europa: Ergebnisse einer vom Kunsthistorischen Institute der Universitat Wien 1913 durchgefuhrten Forschungsreise. Kunstverlag Anton Schroll & Co., 1918.

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BETWEEN TRADITION AND MODERNITY: ARCHITECTURAL TENDENCIES IN THE WORKS OF VASILY MIRZOYAN (LATE 19TH – EARLY 20TH CENTURY)

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Abstract: *Vasily Mirzoyan is an outstanding Armenian architect who worked in the Yerevan Governorate from 1897 to 1910 as a provincial architect and made a major contribution to the development of construction in the region. Churches, administrative, educational, cultural, and entertainment buildings, mansions, apartment houses, engineering facilities, roads, bridges, etc., were built according to the architect's designs. The article, based on archival materials, natural studies, and architectural analysis, reveals the architectural and artistic features of Vasily Mirzoyan's works: appeal to historical styles and Art Nouveau, an address to national structures and motifs, strict logic in the structure of composition systems, and a clear and rational organization of spaces. Innovative interpretations at all stages of design are of great interest. The aim and objectives of the article are to rehabilitate, through the figure of Vasily Mirzoyan, the professional achievements of Armenian architecture and engineering of the nineteenth and early twentieth centuries, as well as to underscore the unquestionable value of information about this historical period that was lost during the Soviet era.*
Keywords: *architectural style, function, building typology, innovation, traditions.*

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Introduction

Vasily Mirzoyan is one of the outstanding legislators of the new architectural school that emerged at the turn of the 20th century. This architectural movement developed a unique style, the definition of which is a combination of European and national Armenian architectural principles of construction, and which left a rich cultural heritage. Vasily Mirzoyan left his memory in the form of beautiful buildings that adorn the streets of Yerevan. All of them are included in the State List of Immovable Historical and Cultural Monuments of Yerevan.

The listed regalia of the architect, as well as the huge list of architectural and engineering projects implemented by him, both in Yerevan and throughout the former Yerevan Governorate, nevertheless leave the name of the architect in unworthy oblivion. In several scholarly works by H. Khalpakhchyan, V. Harutyunyan, and T. Hakobyan devoted to the history and architecture of Yerevan, the name of Vasily Mirzoyan is mentioned; in E. Tigranyan's book, the architect is the subject of an entire chapter. However, the context of these studies is relatively broad, which generally accounts for the concise nature of the information provided about the architect's creative personality [1-6]. More information about him comes from books published by the author of this article, scientific and popular speeches, and scientific and journalistic articles, often included in the theme of Yerevan of the 19th and early 20th centuries [7]. The novelty of this article, in memory of the 160th anniversary of his birth, is the chosen context, focused on the features of the creative style of Vasily Mirzoyan and his innovative methods in architecture. Taking into account his enormous role in the formation of the architecture of this period, this will allow us to trace the path of development of the region's architecture during the time of intensive innovations.

The need to study the work of architects of the 19th and early 20th centuries remains relevant due to filling gaps in the history of modern Armenian architecture and the desire to create a database for pre-design materials for the restoration, reconstruction, and adaptation of architectural monuments.

The purpose of the article is to affirm the professional accomplishments of Armenian architecture and engineering of the 19th and early 20th centuries and to emphasize the indisputable value of this historical period, the significance and documentation of which were largely lost in Soviet times. The objectives of the study include a typological and architectural-artistic characterization of functional groups with the identification of their distinctive features and stylistic priorities during the analyzed period, which will enable further research aimed at identifying continuity between two successive historical epochs.

Materials and Methods

The article is written based on field studies, analysis, and systematization of materials collected in archives, literary sources, periodicals of the 19th–early 20th centuries, and published author's books on the topic of history and architecture of the 19th and early 20th centuries, from which some of the author's own photographs were also borrowed. The main research method is architectural analysis, carried out by studying architectural monuments in nature, measurements, and photographic fixations.

The author investigated the funds of the National Archives of Armenia, the Yerevan History Museum, the State History Museum of Armenia, materials from the personal archive of Vasily Mirzoyan, etc.

Results and Discussion

History. Vasily Mirzoyan (1863/1864, Tiflis – 1925, Yerevan) began his professional career in 1892, the year after graduating from the St. Petersburg Institute of Civil Engineers [1] (Fig.1). In the same year, after a short period of work in Courland, he came to Yerevan, where he began his official and creative work. In the Construction Department of the Yerevan Governorate Administration, he held the post of provincial architect from 1897 to 1910, when he retired from service.

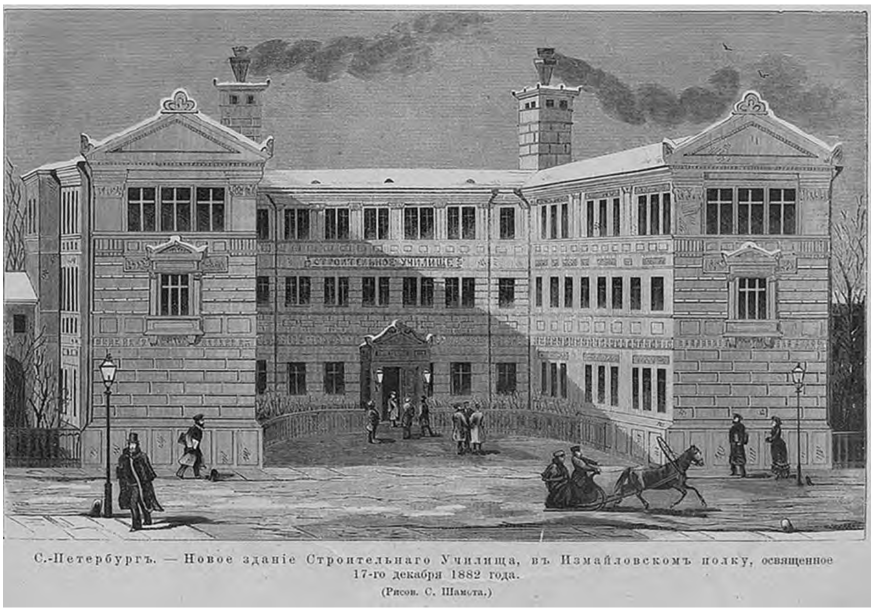

Fig. 1. *The building of the Construction School in St. Petersburg, consecrated in 1882. Photo from Wikipedia - Institute of Civil Engineers*

A list of his works includes all types of public, residential, industrial, and engineering structures. He is the author of the administrative and religious buildings, schools, banks, mansions, apartment houses, factories, bridges, and roads in Yerevan, the towns, and the villages of the governorate [7,8].

He is the Knight of the Order of Saint Stanislav 3rd and 2nd degree, Saint Anna 3rd degree, and "Lion and Sun" 3rd degree.

Buildings. Strength, utility, and beauty (firmitas, utilitas, and venustas)–the basic laws of architecture–are combined in the form-building principles of all the works of Vasili Mirzoyan.

Administrative and public buildings. There are many interpretations, unique solutions, and innovations in their variations, especially for the Armenian architecture of that time. The Treasure House and Treasury Chamber (Fig.2), the Yerevan branch of the State Bank, the Governorate Administration, and the Buniatyan Theatre (co-author Boris Mehrabyan) buildings have been designed with a variety of architectural solutions, taking into account the functional composition, traffic schedule, and respectability of the building. The important position on the city's main streets, in turn, determined the hierarchy of façade forms and decorations that correspond to the urban environment.

Fig. 2. *Treasure house and Treasury Chamber on Nalbandyan street, Yerevan, 1901. Photo by author*

Schools. The architect's archive of works contains projects of educational institutions. This is a large number of primary schools and colleges throughout the territory of the Yerevan Governorate. They are distinguished by a functionally expressed laconic layout and the same facades.

Grand educational institutions, such as the Boys' Gymnasium and Teachers' Seminary, are concentrated in Yerevan. For such large complexes with boarding houses, a typical planning scheme is a spacious inner courtyard, around which the buildings of all functional zones are concentrated. A central axis is also present, along which the main entrance and school hall are located, and a gallery system is used to distribute educational classrooms. In the layout of the Boys' Gymnasium (Figs. 3,4), special attention is drawn to the one-sided, i.e., equal orientation in the placement of all classrooms in the academic buildings.

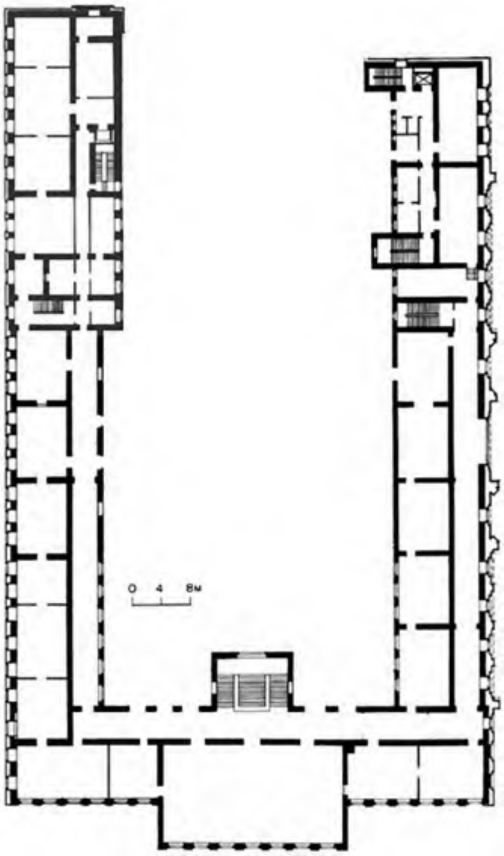

Fig. 3. *Plan of the second floor of the Boy's Classical Gymnasium on Abovyan street, Yerevan, 1916-1920. Geometrical survey*

The second important feature of the layout, which different architects developed at different times, is that, unlike the versions of previous architects, the entrance to the school hall from the street is rationally arranged. This idea made it possible to create an autonomous entrance to the entertainment part of the complex, and a century later, this area of the gymnasium continues its function as Arno Babajanyan Concert Hall.

Mansions and apartment houses. Judging by the cultural heritage preserved in Yerevan, most of the mansions are the work of Mirzoyan. In all cases, it is obvious that homeowners wanted to ask him to design their own home. Of course, the entire range of functional qualities was always successfully solved and satisfied customers. In addition, each building in the layout was distinguished by an individual feature, and the same applies to the external image: not a single building, for example, the mansions of Afrikyan, Fotinov, and Eghiazaryan (Fig.5), repeats another in image, composition, decoration, and stylistic interpretation, being a work of architecture. The same can be said about apartments and multifunctional houses. They retain the specific layout, functional zoning, and distribution of rooms typical of this type of Yerevan house. But each building, separately, is a beautiful and unique piece of art. Interesting associations are caused by the veranda of the apartment of the manager of the Treasury chamber, which connects two exceptionally different forms: the silhouette of the Palladian window and the material of the traditional wooden balcony of the Yerevan house (Fig.6).

Fig. 4. *Portal of Boys' Classical Gymnasium on Abovyan street, Yerevan, 1917-1920. Photo by author*

Fig. 5. *Eghiazaryan mansion on Abovyan street, Yerevan, 1905. Photo by author*

Religious buildings. The list of religious constructions includes not only a variety of shape modeling concepts of architectural solutions but also buildings of different religions: Apostolic, Orthodox (military churches), and Islamic (mosque in Nakhichevan).

The style-forming principles of all religious buildings preserved traditional architectural forms. But certain priorities of the architect are traced in the formation. First of all, the remark refers to the new organization of the entrance, as in the Churches of Surb Astvatsatsin in Gavar (Fig.7) and Vardenis. The bell tower placed in front of the portal leads to the church through a closed vestibule. The church, bell tower, and intermediate volume between them are horizontally longitudinal and vertically built along one axis. Such a functional and compositional solution has a very beneficial effect on the monumental expressiveness of buildings. In many churches, a new window shape was used: vertically elongated three-arched windows, with a central raised arch and three-lobed arcature at the top–a symbol of the Holy Trinity.

Bridges, roads. The National Archives of Armenia have preserved projects of bridges and roads designed by Vasili Mirzoyan. The construction and improvement of engineering structures included covering roads and building bridges across rivers, such as the route from Elenovka to Nor-Bayazet, with a road and a reinforced concrete bridge[1,2]. Bridge trusses were used in the bridge structures, often with a segmental configuration and a polygonal outline of the upper belt.

[1] National Archives of Armenia, fund 19, inventory 1, case 1683.

[2] National Archives of Armenia, fund 94, inventory 3, case 762.

Fig. 6. *Veranda of the apartment of the manager of the Treasury chamber, Yerevan. Photo by author*

Fig. 7. *Church of Surb Astvatsatsin in Gavar, 1900s. Photo from Wikipedia*

Architectural styles. The diversity of architectural and artistic interpretations of the architect's works is expressed in specific compositional techniques and stylistic solutions [8-10]. Thus, in the 1900s, such buildings with different stylistic characteristics were designed and built as the chapel over the tomb of St. Ananias in Yerevan in the national style and the Orthodox church in the village of Kanaker in the traditions of Russian architecture, and the mansions on Astafev Street in Yerevan–Barsegh Eghiazaryan with a neo-Renaissance façade and Vladimir Brazhnikov, in which Art Nouveau is combined with classical forms. An analysis of the buildings constructed by Mirzoyan reveals an impeccable professional mastery of the specifics of architectural forms, ideas, and attributes of style. All this allows for the development of a harmonious interweaving of artistic concepts, in which historical style and a reflection of modernity are undoubtedly simultaneously read (Fig.8).

Neoclassical architecture motifs. The use of the classical order system in the composition reveals a wide range of creative techniques–from reliable citation to original interpretation of Greco-Roman orders. This is the reason for the development of bright individuality and the uniqueness of compositional solutions in the works. From the point of view of the professional skills of the architect, this is one of the testimonies of the virtuoso professional mastery of the architect, always expressed in the logic and harmony of the entire compositional system.

Art Nouveau architecture motifs. Art Nouveau in Mirzoyan's works includes the main directions of style and their combinations with the traditions of Armenian architecture. In Brazhnikov mansion, the author brought together the main composition principles of Art Nouveau and classicism. The building is located in a "relatively homogeneous space", so the entire volume of the building is inscribed in the surrounding environment. The plan is made in a free composition: rooms of different configurations, partly on different levels, are arranged around the central hall, which projects in a semicircular rotunda towards the courtyard. The diversity in the organization of internal spaces is carried out in the external volume of the building, in which straight and curved silhouettes form interesting exteriors viewed from different points. In the volumetric-spatial composition, the accents characteristic of the traditional Armenian home are changed. The usually activated main entrance on the northern wall, although it is solved architecturally significantly, in a certain sense, gives way to the dominance of the entire composition–the balcony-portico on the podium, its presence reinforcing the eastern facade.

Fig. 8. *Apartment building in neo-Gothic style on Abovyan street, project of the 1900s. Recreation and adaptive reuse on Pavstos Buzand street in 2025. Photo by author*

Rational architecture. The ideology of rational architecture, in which the principle "form follows function", is most vividly represented by Kalantaryan country house in Darachichag (present-day Tsaghkadzor), where the landscape and the angular position of the site determined the angular axis of the composition and the angular entrance. The use of relief differences allowed the entrance to be arranged at ground level and the main rooms to be grouped around the hall on the second floor level. There are terraces on the roofs. The utility rooms are isolated from the main entrance and the main group of rooms, and communicate with the garden (Fig.9).

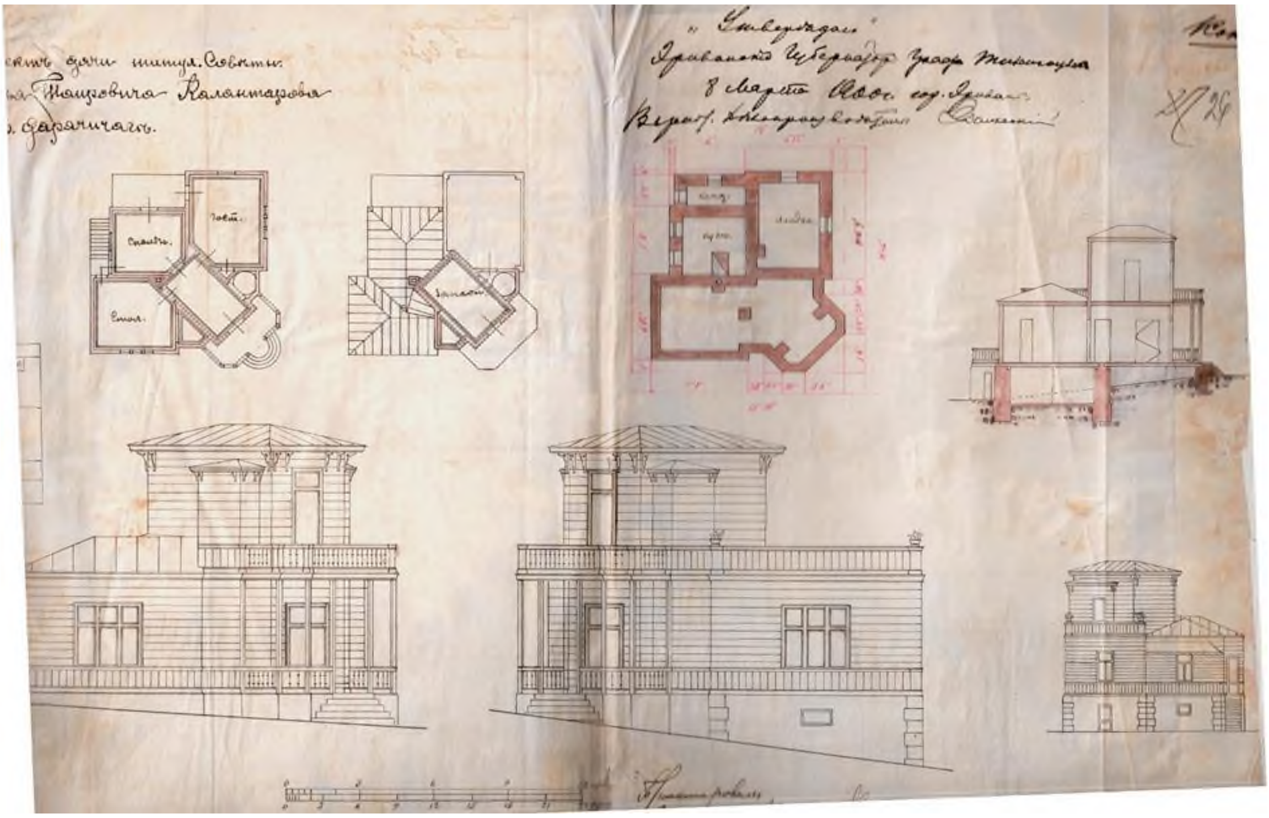

Fig. 9. *Kalantaryan country house, 1900. National Archive of Armenia*

Forms and decorations. In many of Mirzoyan's works, the formulated role is given to decoration, the principle of which corresponds to the basic concepts of historical styles in which the facades of the buildings are made. At the same time, the influence of the medieval monumental architecture of Armenia is undoubted, starting with the local building art–carved ornament on stone. Two architectural concepts interact in the tectonic distribution of decorative compositions in the design of the plane of the walls. The main artistic motifs correspond to the priority architectural themes of the architect: neoclassicism, neo-Gothic, and neo-Baroque, to which Art Nouveau is added, which in total comes down to elegant modillions, rosettes, acanthus leaves, palmettes, and harmonious rhythms of denticles, ovals, and beads. In addition to the characteristic stylistic attributes, the author develops original elements and combinations, such as the sophisticated frieze of the upper part of the facade of Barsegh Eghiazaryan mansion or the mascaron on the portal of the boys' gymnasium. Armenian patterns are harmoniously woven into the compositions, such as a flexible vine with leaves and bunches of grapes between two Corinthian capitals and with a central acanthus lock that decorates the frieze above the window of the Ruben Afrikyan mansion (Fig.10).

Fig. 10. *A fragment of the facade of Afrikyan mansion on Pushkin Street in Yerevan, early 20th century. Photo by author*

Exclusively national ornaments decorate the laconic planes of the walls of Armenian churches and chapels: various braids, interlacing ornaments, and sacred sculptural details. A similar special approach to religious construction is demonstrated by the architecture of the Orthodox military churches in the Kanaker district of Yerevan, where the First Poltava Regiment was located, and in Alexandrapol, which are interpreted in the idea of tent-roofed stone churches of the 16th century. The plasticity of the facades is extremely saturated with elements of Russian national architecture, and at the same time, the artistic language of the ornamental motifs is exceptionally lapidary. Presumably, the mosque in Nakhichevan, about which there is no visual data, was designed in the spirit of Islamic architecture.

Conclusion

Usefulness, design, and beauty–the basic laws of architecture–are combined in the form-generating principles of all the works of Vasily Mirzoyan. The indisputable presence of traditional architectural forms, justified by regional factors and reflecting national artistic images, and their harmonious combination with modern methods of form creation, expressed in historical styles and Art Nouveau–this is how one can generally characterize the priorities of the architect's worldview. Brilliant knowledge of the foundations and specifics of historical architecture and unconditional professional competence in comprehending the strict logic of the structure of artistic systems of national and international architecture allowed the architect to retain creative potential and individuality in the creative rethinking of old and new forms. Therefore, in his buildings, the identification of generally accepted canons of architecture organically flows into his own harmony of proportional balance, using a wide range of creative techniques–from reliable citation to original interpretation of popular architectural motifs. The work of Vasily Mirzoyan is evidence of the high professional level of Armenian architects of the new era, who in the process of searching created an architectural school in which the professional position of the relationship between national architecture and the progressive ideological attitudes of the era is consistently revealed. In general, a detailed analysis of Mirzoyan's architectural and artistic solutions allows us to conclude that, in compliance with the "standards" in the reproduction of stylistic images, a certain tribute is paid to innovative fragments that give the buildings a modern look.

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Conflict of Interest

The author declares no conflicts of interest.

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References

[1]. G. Baranovskiy, Yubileynyy sbornik svedeniy o deyatel'nosti byvshikh vospitannikov Instituta grazhdanskikh inzhenerov (Stroitel'nogo uchilishcha) 1842-1892. Izdatelstvo Instituta grazhdanskikh inzhenerov, Sankt-Peterburg, 1893 (in Russian).
[2]. E. Tigranyan, Hay chartarapetneri gortsuneutyuny Andrkovkasum XIX dari verj - XX dari skizb. Voskan Yerevantsi, Yerevan, 2003 (in Armenian).
[3]. T. Hakobyan, Razvitiye Yerevana posle prisoyedineniya Vostochnoy Armenii k Rossii: Sb. dokumentov (1801-1917). Yerevan State University Publishing House, Yerevan, 1978 (in Russian).
[4]. T. Hakobyan, Yerevani patmutyuny (1879-1917). Yerevan State University Publishing House, Yerevan, 1963 (in Armenian).
[5]. H. Khalpakhchyan, Armyano-russkiye kulturnyye otnosheniya i ikh otrazheniye v arkhitekture. Academy of Sciences of Armenian SSR, Yerevan, 1957 (in Russian).
[6]. V. Harutyunyan, Kamennaya letopis armyanskogo naroda. Sovetakan grokh, Yerevan, 1985 (in Russian).
[7]. M. Gasparyan, The Art of the Old Masters, in: Nicolas Iljine (ed.), Memories of Yerevan. Artguide, Prague, 2023, 196-235.
[8]. M. Gasparyan, Arkhitektura Yerevana 19 i nachala 20 veka. Gorod v prostranstve i vremeni. Palmarium Academic Publishing, 2018 (in Russian).
[9]. M. Dzheremi, Arkhitektura. Putevoditel' po stilyam. Kladez'-Buks, Moscow, 2008 (in Russian).
[10]. V. Kokh, Entsiklopediya arkhitekturnykh stiley. Klassicheskiy trud po yevropeyskomu zodchestvu ot antichnosti do sovremennosti. BMM JSC, Moscow, 2005 (in Russian).

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RESEARCH ON VEHICLE COURSE STABILITY ON MOUNTAIN ROADS

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Abstract: *This study aims to develop a generalized indicator of vehicle course stability for mountain roads that simultaneously accounts for longitudinal and transverse road slopes, small-radius horizontal curves, the tire–road adhesion coefficient, vehicle dynamic parameters, and road transport and operational characteristics. Based on experimental investigations, a force-based calculation scheme describing vehicle motion under mountainous road conditions was developed. On this basis, a dimensionless course stability indicator was formulated, which characterizes vehicle stability as a function of road geometric parameters. For mountain roads with large longitudinal gradients and small-radius horizontal curves, an integral indicator combining road geometry and vehicle dynamics was obtained to assess vehicle motion stability on typical mountainous road sections.*

Keywords: *automobile, course stability, longitudinal and transverse slope, centrifugal force, turning radius, adhesion coefficient.*

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Introduction

Course stability is an essential component of active vehicle safety and reflects the ability of a vehicle to maintain a prescribed direction of motion under the influence of external disturbances. Vehicle operation in mountainous terrain is characterized by significant longitudinal and transverse road slopes, as well as frequent horizontal curves with small turning radii. Under such conditions, vehicle course stability is substantially altered. A vehicle traveling on a mountain road is simultaneously subjected to the longitudinal component of gravitational force, lateral inertial effects associated with mass distribution, and centrifugal forces arising during cornering.

The influence of road transport and operational indicators on vehicle motion dynamics under mountainous conditions is of particular importance. In most existing long-term studies, vehicle motion equations are formulated for flat road surfaces. However, according to the Construction Standards of the Republic of Armenia (RA Construction Standards)[1], road transport and operational indicators include pavement roughness (IRI index), a wide range of tire–road adhesion coefficients, pavement elasticity characteristics, transverse slopes for water drainage, and other parameters that are not explicitly incorporated into conventional vehicle motion equations.

At the same time, modern vehicles are capable of maintaining relatively high speeds even under difficult road-operating conditions due to the performance of contemporary internal-combustion engines. Under such circumstances, vehicle dynamics–and especially course stability–change significantly. This is confirmed by the substantial increase in road traffic accidents on the roads of the Republic of Armenia involving lane departure and roadway run-off, often resulting in severe consequences. Notably, many such accidents also occur on horizontal road sections [1,2].

Vehicle dynamics under the combined influence of these factors remain insufficiently studied; therefore, the present research is of both theoretical and practical significance.

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[1] HH SHN 32-01-2022 "Avtomobilayin chanaparhner" Hayastani Hanrapetutyan shinararakan normer, 2022 (in Armenian).

Materials and Methods

In the Republic of Armenia, the principal technical parameter for highway design in mountainous terrain is the permissible design speed: 70–90 km/h for categories IC–IA, 60 km/h for category II, 50 km/h for category III, and 40 km/h for category IV highways[2].

The design speed is defined as the maximum possible speed of a single vehicle that can be ensured by the main elements of the road under favorable weather conditions and normative values of the tire–road surface adhesion coefficient, while ensuring vehicle stability and driving comfort[3] [1].

In mountainous terrain, sharp changes in road alignment are permitted on category II–IV highways, resulting in the appearance of serpentines. The radii of horizontal curves in such sections may be as small as 15–30 m (depending on the design speed of 15–30 km/h) and may have a one-sided cross slope of up to 60 ‰ [4].

Even at relatively low speeds, vehicles operating in mountainous conditions experience significant lateral and longitudinal inertial loads that directly affect course stability.

The issue is particularly relevant for road trains, for which studies under mountain operating conditions are extremely limited. This is especially important for the Republic of Armenia, where approximately 75% of foreign trade cargo turnover is carried out by road transport, including road trains [1,2].

The objective of this study is to determine integral and dynamic indicators of course stability under mountain driving conditions characterized by small-radius curves and significant longitudinal and transverse slopes.

An integral indicator of course stability is proposed that incorporates both vehicle dynamics and road geometric parameters.

The research methodology is based on deriving an analytical expression for vehicle course stability under conditions of variation of the main factors that determine course stability in real operating conditions. Russian researchers assess vehicle course stability [3-5] using the integral steering wheel rotation angle during vehicle trajectory correction. In European countries, the assessment of course stability is based on the ISO 7401 and ISO 4138 standards[5,6,7]. Both approaches are acceptable and have been developed for flat road conditions. However, there are no studies addressing roads with complex mountainous terrain [6,7].

It is necessary to conduct analyses for continuously varying road parameters, such as the adhesion coefficient, vehicle speed, and the radius of horizontal curves, among others. As motivating factors, the condition of the road pavement, icing, crosswinds, and variable climatic conditions are considered, which in aggregate influence changes in the value of the adhesion coefficient.

Results and Discussion

The analysis of vehicle course stability on mountain roads is based on force equilibrium during straight-line and curved motion in the presence of longitudinal slopes. Under these conditions, the vehicle is affected by kinematic forces associated with curved motion and by gravitational forces acting at an angle to the road surface.

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[2] HH SHN 32-01-2022 "Avtomobilayin chanaparhner" Hayastani Hanrapetutyan shinararakan normer, 2022 (in Armenian).
[3] Ibid.
[4] Ibid.
[5] ISO 7401. This International Standard specifies open-loop test methods for determining the transient response behaviour of road vehicles. 2011.
[6] ISO 4138. This International Standard specifies open-loop test methods for determining the steady-state circular driving behaviour of passenger cars. 2015.
[7] ISO 7975. Passenger cars - Braking in a turn - Open-loop test method *specifies an open-loop test.* 2019.

Experimental investigations were carried out using the KP-514 mobile road laboratory and the PKRS-2 measurement system. A gyroscopic sensor was used to measure road azimuth, curvature radius, and longitudinal and transverse slopes, with a measurement accuracy of ±10%.

Experimental studies were carried out using a mobile laboratory vehicle KP-514 and a PKRS-2 complex (Fig.1). The change in the angle of the center of gravity vector during the straight course of the vehicle was considered as the vehicle drift, and the deviation angle was considered as a change in the course direction.

a. **b.**

Fig. 1. *KP-514 and PKRS-2 complex mobile laboratory.*
a. *the laboratory vehicle on a steep descent,* b. *the laboratory vehicle on a small-radius curve landing section*

The research was conducted on a characteristic section of 808 m of the national highway H-3: Yerevan-Garni-Geghard Monastery (38.1 km). The changes in the azimuth of the road traveled during straight travel and turns were studied.

1. The road passes through rugged terrain and has large longitudinal slopes and small-radius horizontal curves.
2. Changes in the vehicle's course stability were presented in tabular form (Table).

Table. The change in the course stability coefficient according to the sections of the road studied

Measured length of the road (m.)	Beginning (m)	The end (m)	Azimuth A°		The deviation of A°	Inclination angle (i %)	Course stability coefficient (K_c.)	Road section characteristics
			on the road at the beginning	at the end of the road				
20	0	20	195.440	198,360	2.92	0	1.12	straight uneven
53	20	53	198.360	200.430	2.07	7	0.695	large longitudinal slope
343	53	343	200.430	200.460	0.03	4	0.53	landing with a small radius curve
390	343	390	183.970	183.780	0.190	3	0.65	horizontal curve with a small radius
582	390	582	183.780	185.820	2.040	8	0.57	landing with a small radius curve
662	582	662	185.810	185.960	0.140	9	0.93	small radius uphill curve
808	662	808	185.960	184.270	1.620	1	1.05	low visibility

Measured data showed that the deviation angle varied from 0.03° to 2.92°. Vehicle speed ranged from 35 to 51.3 km/h, while the adhesion coefficient varied from 0.49 to 0.70. Road slopes ranged from 0 to 9%, and curve radii varied between 25 and 50 m.

The goal of the research is to develop a generalized indicator of automobile course stability that simultaneously takes into account the influence of the following factors:

- longitudinal slope of the road - i,
- the turning radii - R,
- transverse slopes - i_0 ,
- the adhesion coefficient - φ,
- the dynamic parameters of the car - D.

To solve the problem posed, it is necessary to:

1. Create a calculation scheme for the forces that affect a car when making a turn on a slope.
2. To develop a dimensionless indicator of course stability (K_c), which will reflect the stability of the vehicle to lateral obstacles, according to the geometric parameters of the road:

$$K_c = f\,(\delta_{\sum} \cdot \alpha_y \cdot R \cdot i \cdot \varphi), \quad (1)$$

where, $\delta_{\sum}$ to the steering wheel is the total angle of rotation, α_y is the lateral acceleration, R is the turning radius, i is the longitudinal slope of the road, φ is the coefficient of adhesion.

To investigate the calculation scheme, let's consider a coordinate system related to the road, with the forces acting on the car in the x,y,z coordinate system (Fig.2) [7-10]:

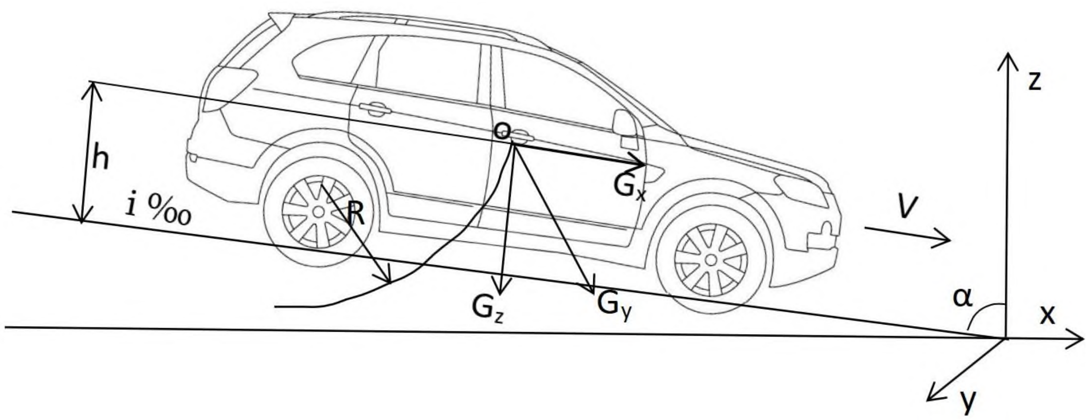

Fig. 2. *Forces Acting on a Vehicle During Cornering on a Longitudinally inclined Road*

The x-axis is directed in the direction of the longitudinal slope of the road, the y-axis is directed in the direction of the transverse slope of the road (direction of centrifugal forces), and the z-axis is perpendicular to the road.

In this system, the following forces act on the automobile:

1. The force of gravity, G = m·g, which has 2 components:
   - longitudinal $G_x = G \cdot \sin i$, (2)
   - normal $G_z = G \cdot \cos i$, (3)

where m is the mass of the car, g is the acceleration of gravity, i is the longitudinal slope of the road.

2. The centrifugal force of inertia F_c arises when moving along an arc of radius R and velocity v:

$$F_c = \frac{mv^2}{R}. \quad (4)$$

This force causes the car to skid and tends to turn the car perpendicular to the outside of the turn.

3. The lateral grip force of the tires F_y is the resistance of the road directed in the opposite direction of the centrifugal force and ensures that the car is kept in the intended trajectory, which ensures the car's resistance to sideslip:

$$F_y=\varphi \cdot G_z \, . \tag{5}$$

4. The lateral bending force (lateral force) can partially counteract the force F_c:

$$G_y=G \cdot sin\alpha \, . \tag{6}$$

5. The resistance force acting on the wheels is distributed to each wheel in proportion to its normal load:

$$\Delta Z_{1\text{-}4}=\frac{m \cdot h \cdot \alpha_y}{l}, \tag{7}$$

where h is the height of the center of gravity, l is the track width (the distance between wheels on the same axle).

The stability condition of the car is fulfilled if the sum of the lateral forces does not cause an increase in the lean angle. The lateral stability condition must satisfy the following expression:

$$F_y+G_y=F_c \, , \tag{8}$$

or in the open form:

$$\varphi \cdot G_z+G \cdot sin\alpha=\frac{mv^2}{R}. \tag{9}$$

From here, you can calculate the permissible speed of a car when turning on a mountain slope:

$$V_\text{p}=\sqrt{R \cdot g \cdot (\varphi \cdot cosi+sin\alpha)} \, . \tag{10}$$

Let's consider the dimensionless indicator Kc for vehicle movement in different modes and evaluate the vehicle's course stability based on the road's longitudinal slope (i), movement's radius of curvature (R), and transverse slope (α).

Using expressions (9) and (10), we can derive the vehicle's course stability rating (K_c):

$$K_c=\frac{F_y+G_y}{F_c}=\frac{\varphi \cdot g \cdot cosi+g \cdot sin\alpha}{v^2/R}, \tag{11}$$

The stability criterion is defined as follows:

- $K_c > 1$: stable vehicle motion,
- $K_c = 1$: motion at the stability limit,
- $K_c < 1$: loss of tire adhesion and onset of sideslip.

Using the measured data, we calculate the vehicle's course stability according to formula (11) for the area:

$$K_c=\frac{\varphi \cdot g \cdot cosi+g \cdot sin\alpha}{v^2/R}=\frac{0.47 \cdot 9.8 \cdot 0.999+9.8 \cdot 0.017}{14.6^2/50}=\frac{4.6+0.17}{4.26}=1.12 \, .$$

The remaining precincts were calculated in the same way.

It means that the stability of the car is sufficient: $K_c=1.12$ is greater than 1 according to formula (11). The calculation of the course stability is correct, and it is confirmed by experiments.

According to the data in the table, we construct a diagram of the change in the vehicle's course stability coefficient, K_c, according to the research site (Fig. 3).

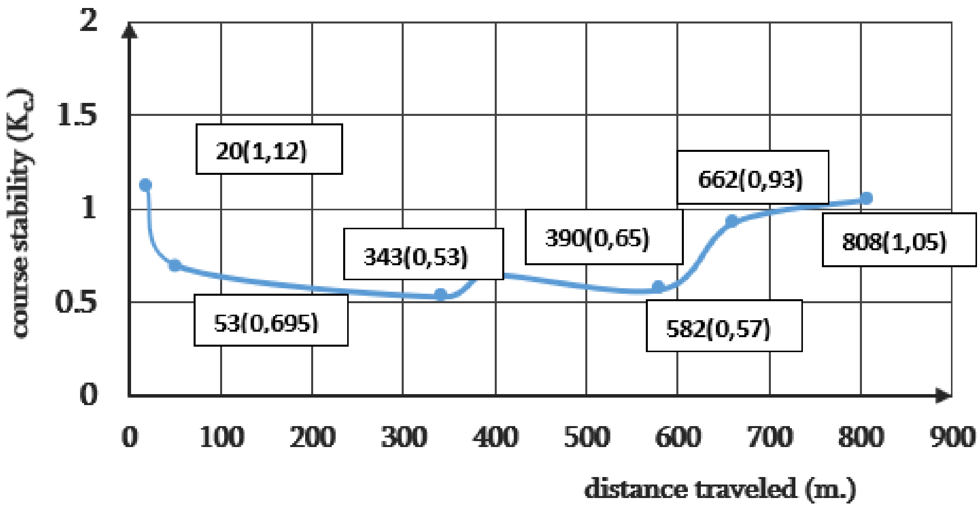

Fig. 3. *Vehicle stability control Diagram of change according to the tested site*

Conclusion

1. The proposed dimensionless coefficient K_c represents an integral indicator combining road geometric parameters and vehicle dynamic characteristics. It enables assessment of vehicle motion stability on mountain road curves.
2. Application of the proposed method makes it possible to identify hazardous road sections (black spots) in mountainous terrain and can be effectively used in the development of traffic safety improvement measures.

Conflict of Interest

The authors declare no conflicts of interest.

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References

[1]. M. Park, S. Yim, Comparative Study on Coordinated Control of Path Tracking and Vehicle Stability for Autonomous Vehicies on Low-Friction Roads. Actuators, 12 (11), 2023. Doi: https://doi.org/10.3390/act12110398

[2]. J. Chen, R. Wang, W. Liu, D. Sun, Y. Jiang, R. Ding, A Review of Resent Advances in Roll Stability Control on-Road and off-Road Vehicles. Applied Sciences, 15 (10), 2025. Doi: https://doi.org/10.3390/app15105491 .

[3]. A.S. Litvinov, Upravlyayemost i ustoychivost avtomobilya. Mashinostroyeniye, Moscow, 1971 (in Russian).

[4]. V.A. Ilarionov, Stabilizatsiya upravlyayemykh koles avtomobilya (2nd ed.). Transport, Moscow, 1966.

[5]. A.S. Litvinov, Y.Y. Farobin, Avtomobil: Teoriya ekspluatatsionnykh svoystv. Mashinostroyeniye, Moscow, 1989 (in Russian).

[6]. R. Rajamani, Vehicle Dynamics and Control (2nd ed.). Springer, Mechanical Engineering Series, New York, 2012.

[7]. S.V. Bakhmutov, Nauchnyye osnovy parametricheskoy optimizatsii avtomobilya po kriteriyam upravlyayemosti i ustoychivosti. Doctoral thesis, Moscow, 2001 (in Russian).

[8]. Y.Y. Farobin, V.S. Shuplyakov, Otsenka ekspluatatsionnykh svoystv avtopoyezdov dlya mezhdunarodnykh perevozok. Transport, Moscow,1983 (in Russian).

[9]. Y.M. Pevzner, G.G. Gridasov, A.D. Konev, et al., Kolebaniya avtomobilya. Mashinostroyeniye, Moscow, 1979 (in Russian).

[10]. R.N. Jazar, Vehicle Dynamics: Theory and Application. Springer Nature, 2025.

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