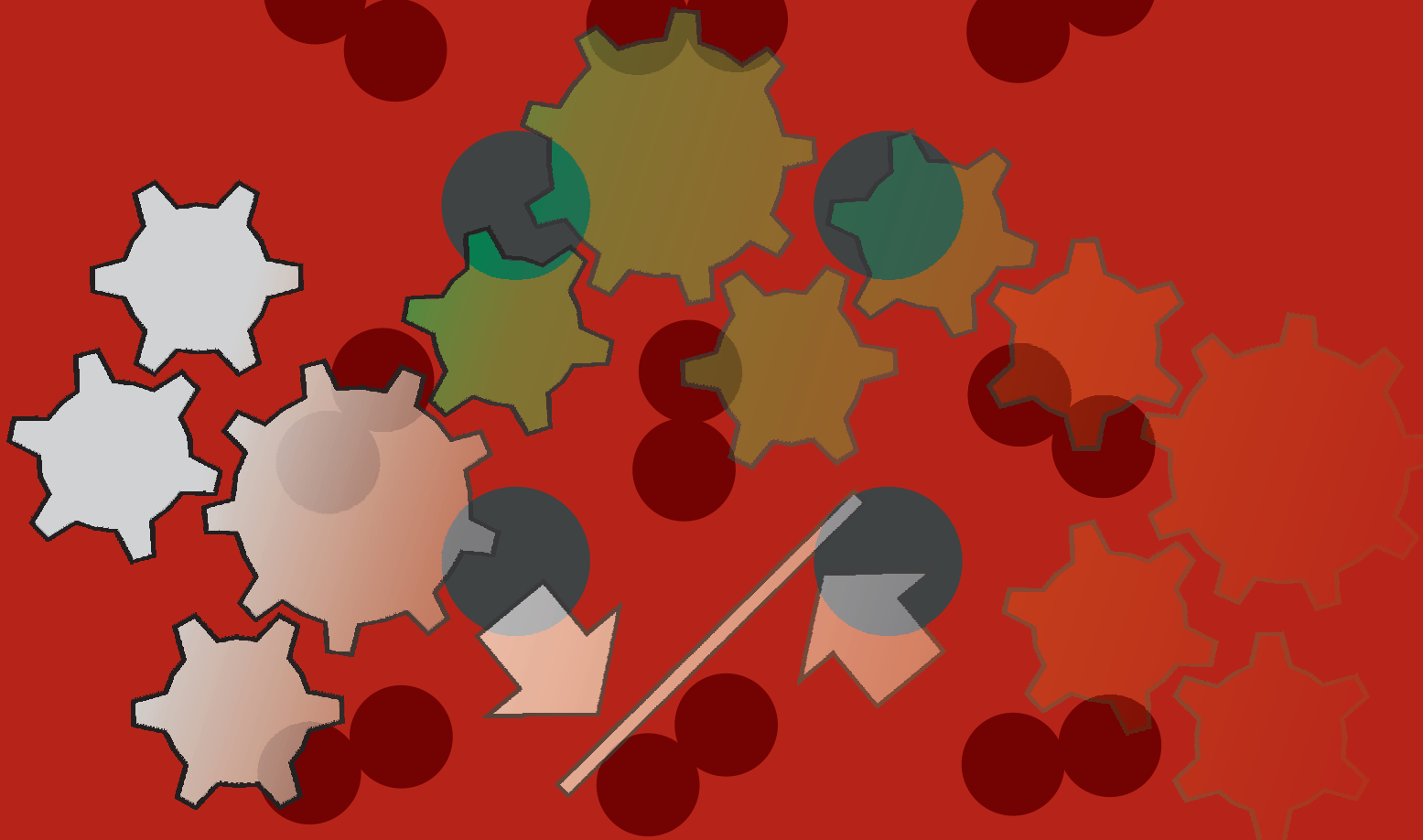
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Forecasting monthly road accidents in selected cities of wielkopolska using neural networks

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Keywords: road accidents, neural networks, time series forecasting, forecast accuracy, urban traffic safety.
Abstract: Accurate forecasting of road accidents is essential for urban traffic safety management and preventive planning. This study uniquely integrates meteorological and accident data across five mid-sized Polish cities, providing city-specific forecasting insights. Findings suggest city-specific neural network models can guide targeted interventions, particularly in small vs. large urban areas. This study analyzes monthly road accident data from five cities in the Wielkopolska region of Poland—Piła, Konin, Leszno, Poznań, and Kalisz—covering the period 2018–2024, and evaluates the performance of neural network-based forecasts over 6- and 12-month horizons. The dataset includes meteorological variables (temperature, precipitation, snow cover, humidity, wind, sunshine) and detailed accident counts, distinguishing between minor, serious, and fatal accidents. Descriptive statistics reveal significant differences across cities: Poznań exhibits the highest average monthly accidents and variability, while Piła records the lowest mean with several months of zero accidents. Forecast accuracy metrics (MAE, RMSE, MAPE) indicate that neural network models provide reasonable predictions in absolute terms, particularly for larger cities, while relative errors are high in smaller cities due to low accident baselines. Extending the forecast horizon from 6 to 12 months generally reduces accuracy, although some medium-sized cities show minor improvements, likely reflecting annual seasonal patterns. The results highlight the importance of city-specific forecasting strategies, where absolute errors guide planning in large urban centers and relative errors are critical in smaller cities. The study demonstrates the practical applicability of neural networks in urban accident prediction, while also identifying limitations related to low-frequency events, model interpretability, and available predictors.

1 Introduction

Road traffic accidents constitute a major public safety concern worldwide, resulting in fatalities, injuries, and substantial economic costs. In Poland, despite long-term efforts to improve road safety, accident frequency and severity continue to vary significantly across regions and urban areas. Accurate forecasting of road accidents is essential for urban planning, traffic management, and preventive interventions, enabling authorities to allocate resources efficiently and implement targeted safety measures.

Recent studies have demonstrated the potential of machine learning methods, including artificial neural networks, in predicting traffic accidents. Neural networks are particularly suitable for modeling complex, nonlinear relationships between meteorological, temporal, and traffic-related variables and accident occurrences. Prior research has applied such approaches to various scales, from national-level analyses to city-specific forecasting, highlighting improvements over traditional statistical models in short- and medium-term prediction accuracy.

This study focuses on five cities in the Wielkopolska region of Poland: Piła, Konin, Leszno, Poznań, and Kalisz. The selected cities differ in population size, urban infrastructure, and traffic volume, providing a diverse set of contexts for analyzing accident patterns. The analysis employs monthly data for the period 2018–2024, including weather variables (e.g., temperature, precipitation, snow cover, wind, and sunshine), and detailed records of traffic accidents with distinctions by severity. This comprehensive dataset allows for both descriptive statistical analysis and the development of predictive models using neural networks.

Despite growing interest in machine learning applications for road safety, most studies focus either on national-level analyses or short-term daily/hourly predictions. City-specific monthly forecasting using neural networks, especially in medium-sized European cities and with explicit inclusion of meteorological variables, remains relatively underexplored in the Polish context. This gap is particularly relevant given Poland's persistently high road fatality rates compared to many EU countries and the need for localized, actionable predictions to support municipal traffic safety policies.

The primary objectives of this study are twofold. First, to quantify and compare the descriptive characteristics of monthly road accidents across the five cities, highlighting differences in mean accident frequency, variability, and severity. Second, to evaluate the accuracy of neural network-based forecasts over 6- and 12-month horizons, using standard error metrics (MAE, RMSE, MAPE) to assess both absolute and relative predictive performance. The study also

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examines how forecast accuracy varies with city size and accident baseline, providing insights into the practical applicability of neural network models in urban traffic safety planning.

By integrating regional accident data, meteorological variables, and advanced forecasting techniques, this research contributes to the evidence base for data-driven traffic safety management in medium- and large-sized Polish cities. The findings are relevant for policymakers, urban planners, and researchers seeking to optimize accident prevention strategies and improve the effectiveness of predictive modeling in transport safety contexts. Although prior studies applied neural networks at national scales, city-specific monthly forecasting remains underexplored in Poland.

2 Literature review

Research on road safety (RS) in Poland has traditionally focused on statistical analyses of accident rates, infrastructure, and technical and environmental factors. In recent years, however, there has been a clear expansion of the research field to include a social perspective, covering the opinions of road users, the evaluation of preventive measures, social campaigns, legal solutions, and the functioning of institutions responsible for RS. This direction is consistent with a systemic approach, in which road safety is seen as the result of interactions between people, vehicles, infrastructure, and the institutional environment.

Poland remains one of the European Union countries with relatively high rates of road accidents and fatalities per capita, which has made road safety one of the key areas of public policy for years [1,2]. Analyses show that despite systematic improvements in road infrastructure since EU accession, the development of the transport network also generates new risks, resulting, among other things, from increased traffic intensity, travel speeds, and diversity of road users [1,3]. In this context, public acceptance of risk-reducing measures such as speed controls, changes in traffic organization, and stricter legal regulations is becoming increasingly important.

Social campaigns are one of the basic instruments of preventive action in the area of road safety in Poland. However, their effectiveness remains a subject of debate, mainly due to methodological difficulties in clearly attributing changes in the behavior of road users to specific communication activities [4,6]. Surveys conducted among young adults (aged 18–25) show that respondents are widely exposed to road safety campaigns, primarily through television (approx. 88%), the Internet, and outdoor advertising [2]. At the same time, respondents rate the level of safety on Polish roads as low or moderate, pointing to reckless driving, inappropriate speed, and the condition of infrastructure as the main sources of danger.

The declared impact of the campaigns on the behavior of road users varies demographically. In the study by Goniewicz et al., approximately 67% of women and 42.5% of men declared a change in behavior under the influence of the campaigns, which suggests significant differences in perception and behavior [2]. In turn, analyses of campaigns promoting the use of seat belts and child seats indicate that long-term, consistent education supported by behavior monitoring can lead to a lasting improvement in safety indicators, including a decrease in the number of accident victims [5]. At the same time, the authors emphasize the lack of clear, “hard” measures of campaign effectiveness and discrepancies in assessments of their real impact on the level of road safety on a national scale [4].

An important area of research is the analysis of opinions on legal regulations, especially with regard to vulnerable road users. Studies on pedestrian safety indicate that the existing legal provisions can be considered generally sufficient, but their effectiveness in practice depends on the interpretation of the rules by drivers, pedestrians, and law enforcement authorities [6,7]. The role of pedestrian infrastructure is also emphasized, which in many locations does not meet safety standards, limiting both the actual safety and the subjective sense of protection of road users.

At the institutional level, provincial traffic centers (WORD) play an important role, providing re-education training for drivers who violate traffic regulations and improvement activities for examiners. The scale of these initiatives indicates a growing acceptance of an educational and corrective approach, complementing traditional repressive measures [8]. At the same time, municipal police forces are involved in local preventive activities, including parking control, information campaigns, and educational programs aimed at children and young people [9]. However, studies on the perception of these formations reveal an ambivalent social image, while recognizing their importance for maintaining order and safety in urban areas [10,11].

From the perspective of road users, hazards are increasingly associated not only with infrastructure and driver behavior, but also with distraction caused by the use of mobile devices. Studies indicate the widespread use of mobile phones by both pedestrians and drivers, with an awareness of the risks and a tendency to downplay them [12]. This phenomenon provides an important social background for the acceptance of regulations restricting the use of mobile devices in traffic.

In comparative terms, surveys conducted in India show high public support for tightening regulations, strengthening the penalty system, and raising exam requirements, regardless of the respondent's status as a driver or pedestrian [13]. These results correspond to the need observed in Poland for more decisive action in favor of road safety, although there is still a lack of nationwide studies that would systematically map Poles' opinions on tightening regulations, supervision, and traffic control.

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Recent advances in road accident forecasting have shifted from traditional statistical methods (e.g., Poisson and negative binomial regression) toward machine learning techniques, particularly artificial neural networks (ANNs), due to their ability to capture complex, non-linear relationships [14–16]. Several studies have successfully applied multilayer perceptrons (MLP), recurrent neural networks (RNN), and long short-term memory (LSTM) models to predict accident frequency at national, regional, or corridor levels, often incorporating weather, traffic volume, and temporal variables [17–19].

However, most research focuses on daily or hourly predictions, while monthly city-level forecasting remains less common. Studies that do address monthly scales typically analyze larger metropolitan areas or entire countries, with fewer examples from medium-sized cities in Central and Eastern Europe [15,18]. Meteorological factors such as temperature, precipitation, and snow cover have been consistently identified as significant predictors, especially in regions with distinct seasonal weather patterns [18,19].

In the Polish context, existing forecasting efforts have primarily relied on trend models or econometric approaches [15,16]. Neural network-based monthly predictions for individual cities, integrating local meteorological data, have not been widely reported. This study addresses this gap by developing and evaluating city-specific MLP models for five diverse cities in the Wielkopolska region.

3 Materials and methods

The analysis uses monthly data from five cities in the Wielkopolska region of Poland—Piła, Konin, Leszno, Poznań, and Kalisz—covering the period 2018–2024. The dataset comprises meteorological and traffic-related variables extracted from city-level records. For each city, the dataset includes the following monthly variables: mean temperature, minimum temperature, total precipitation, maximum snow cover, mean humidity, mean wind speed, sunshine duration, number of traffic incidents, total number of road accidents, number of accidents with minor injuries, number of accidents with serious injuries, and number of fatal accidents (Table 1-5, Figure 1).

Table 1 Statistic data for Piła [20,21]

Year	Mont	Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine	Number of incidents	Number of accidents	Number of accidents with minor injuries	Number of accidents with serious injuries	Number of accidents with fatalities
2018	I	1.5	-0.6	50.1	13.0	88.7	2.6	32.3	69	2	1	1	0
	II	-3.0	-5.9	5.0	2.0	81.2	1.9	107.5	38	0	0	0	0
	III	0.0	-3.8	31.7	5.0	75.7	2.5	137.1	65	1	1	0	0
	IV	12.1	5.9	53.9	0.0	70.4	2.4	265.4	60	1	0	1	0
	V	17.4	10.2	9.5	0.0	57.9	2.4	351.6	65	1	1	0	0
	VI	18.6	12.2	20.3	0.0	60.9	2.3	268.0	54	0	0	0	0
	VII	20.6	14.1	113.1	0.0	66.3	2.1	284.3	73	1	0	1	0
	VIII	20.3	13.9	8.8	0.0	63.9	1.9	285.6	69	1	1	0	0
	IX	15.3	10.0	18.6	0.0	70.5	1.9	207.7	71	6	5	0	1
	X	10.0	5.0	22.2	0.0	77.9	2.2	169.8	70	1	0	1	0
	XI	4.6	2.1	6.7	0.0	87.0	1.9	57.3	62	7	4	4	0
	XII	2.6	0.5	37.5	3.0	90.2	2.3	15.5	91	4	2	1	1
2019	I	-0.2	-2.3	29.1	1.0	89.0	2.5	38.8	63	2	3	0	0
	II	2.9	-0.4	5.9	0.0	81.0	2.3	93.8	54	0	0	0	0
	III	5.9	2.2	23.4	0.0	77.3	2.7	115.3	83	2	0	2	0
	IV	10.3	3.7	2.1	0.0	53.7	2.9	282.3	71	0	0	0	0
	V	12.2	6.9	51.2	0.0	68.6	2.3	181.5	66	1	1	0	0
	VI	22.2	14.5	14.5	0.0	57.0	2.4	349.9	69	0	0	0	0
	VII	19.0	13.4	38.4	0.0	62.7	2.4	233.4	72	0	0	0	0
	VIII	20.0	13.7	24.6	0.0	63.5	1.8	255.7	66	0	0	0	0
	IX	13.5	9.2	99.0	0.0	78.4	2.2	139.2	68	3	3	0	0
	X	10.0	6.1	38.9	0.0	84.6	1.8	119.2	83	1	1	0	0
	XI	5.7	3.5	52.7	0.0	89.8	2.4	43.5	76	1	0	0	1
	XII	3.1	0.8	20.7	0.0	86.8	2.2	44.8	71	3	1	2	0
2020	I	3.1	0.7	38.7	0.0	87.6	2.5	54.4	63	0	0	0	0
	II	4.3	1.5	56.0	0.0	80.0	2.9	61.6	56	2	1	1	0
	III	4.4	0.0	33.8	0.0	68.0	2.5	190.7	54	1	0	0	1
	IV	8.7	0.9	1.6	0.0	53.8	2.3	289.5	29	1	1	0	0
	V	11.4	5.6	48.1	0.0	65.3	2.5	241.7	45	1	1	0	0
	VI	18.2	13.2	102.9	0.0	71.1	2.2	209.7	62	1	1	0	0
	VII	17.9	12.1	51.6	0.0	68.5	2.1	257.9	58	2	1	2	0
	VIII	20.1	14.1	40.8	0.0	69.2	1.9	260.8	70	3	2	0	1
	IX	14.4	8.7	66.7	0.0	81.4	1.8	212.6	60	3	1	2	0
	X	10.4	7.3	67.7	0.0	86.2	2.0	83.3	56	4	2	1	1
	XI	6.1	3.9	8.2	0.0	89.6	2.0	44.6	51	1	0	1	1
	XII	2.1	0.1	37.0	2.0	89.7	2.4	29.7	81	1	1	0	0
2021	I	-0.8	-2.6	62.1	15.0	90.3	2.1	26.5	59	0	0	0	0
	II	-1.3	-4.9	27.3	15.0	84.1	2.1	100.2	50	0	0	0	0
	III	3.5	-0.5	24.4	0.0	76.9	2.1	131.9	47	0	0	0	0

	IV	5.9	0.7	38.8	4.0	70.4	2.3	163.2	52	3	2	1	0
	V	12.0	6.5	69.8	0.0	70.9	2.3	222.1	79	0	0	0	0
	VI	19.8	12.5	24.8	0.0	61.5	2.1	327.4	74	3	3	0	0
	VII	20.7	15.4	42.8	0.0	71.3	2.1	233.0	59	0	0	0	0
	VIII	17.2	12.3	26.2	0.0	70.0	2.2	183.7	67	1	1	0	0
	IX	14.7	10.0	16.4	0.0	76.0	2.0	168.4	72	0	0	0	0
	X	9.3	4.9	32.9	0.0	81.8	2.0	152.3	69	2	1	3	0
	XI	5.5	3.6	44.7	1.0	92.1	2.2	24.2	71	0	0	0	0
	XII	-0.7	-3.2	36.0	12.0	91.4	2.2	29.6	60	0	0	0	0
2022	I	1.6	-0.7	48.4	4.0	88.7	2.8	54.7	50	1	1	0	0
	II	3.7	1.1	74.2	0.0	82.3	*3.1*	75.7	44	2	1	0	1
	III	3.4	-2.6	0.1	0.0	63.3	2.0	241.9	64	0	0	0	0
	IV	7.3	1.9	30.7	0.0	64.8	2.6	199.6	67	1	0	1	0
	V	13.4	6.9	42.8	0.0	63.5	2.3	259.1	70	2	2	0	0
	VI	18.7	12.1	30.5	0.0	65.0	2.1	305.8	54	1	1	0	0
	VII	19.2	13.0	36.4	0.0	64.6	2.4	288.8	61	0	0	0	0
	VIII	21.6	15.9	60.2	0.0	66.6	1.9	245.5	59	4	4	0	0
	IX	12.6	8.1	36.4	0.0	76.9	1.9	165.3	60	3	3	0	0
	X	10.7	6.6	33.8	0.0	89.0	1.7	116.5	59	1	0	1	0
	XI	4.5	2.4	16.6	5.0	90.7	2.1	49.8	48	3	1	2	0
	XII	0.7	-1.3	32.8	1.0	90.3	2.2	18.1	61	0	0	0	0
2023	I	3.1	1.3	56.3	4.0	88.9	2.4	18.5	48	3	2	1	0
	II	1.8	-1.0	33.0	1.0	81.6	2.5	73.9	43	0	0	0	0
	III	4.0	0.6	58.4	3.0	79.9	2.3	107.7	62	3	3	1	0
	IV	7.9	3.2	31.8	0.0	72.3	2.3	167.8	50	2	2	0	0
	V	13.1	6.3	13.0	0.0	57.9	2.5	318.5	64	1	0	1	0
	VI	18.5	11.7	57.3	0.0	59.3	2.1	295.6	61	0	0	0	0
	VII	18.9	12.5	67.5	0.0	64.2	2.1	258.0	49	2	2	0	0
	VIII	18.8	14.2	114.5	0.0	76.0	1.9	195.7	67	4	3	1	0
	IX	17.5	11.1	6.3	0.0	75.3	1.6	281.0	76	3	2	1	0
	X	10.1	6.6	76.1	0.0	85.6	2.2	72.8	67	3	1	3	0
	XI	3.9	1.0	81.6	6.0	89.4	2.1	48.1	72	0	0	0	0
	XII	2.3	0.0	78.5	7.0	89.5	2.7	25.6	57	2	1	1	0
2024	I	0.2	-2.6	47.9	7.0	85.9	2.7	51.8	63	0	0	0	0
	II	5.5	2.9	75.4	0.0	88.3	2.6	34.1	65	1	0	0	2
	III	6.9	3.0	19.3	0.0	78.5	2.3	130.2	57	0	0	0	0
	IV	10.3	4.7	29.6	0.0	69.9	2.3	179.9	60	1	1	0	0
	V	16.8	10.3	59.2	0.0	61.4	2.5	317.7	63	1	1	0	0
	VI	17.9	11.8	35.7	0.0	69.7	2.1	269.4	53	0	0	0	0
	VII	19.4	13.6	129.8	0.0	71.4	1.9	267.9	60	0	0	0	0
	VIII	19.8	13.7	26.4	0.0	68.2	1.8	304.8	47	1	1	0	0
	IX	16.8	11.7	27.8	0.0	69.7	2.4	232.9	67	1	1	0	0
	X	10.2	6.7	24.3	0.0	82.0	2.1	113.9	74	0	0	0	0
	XI	4.1	2.0	36.4	1.0	90.2	2.2	33.6	54	4	3	1	1
	XII	3.4	1.8	26.0	0.0	92.7	2.4	23.6	59	2	1	1	0

Table 2 Statistic data for Konin [20,21]

Year	Month	Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine	Number of incidents	Number of accidents	Number of accidents with minor injuries	Number of accidents with serious injuries	Number of accidents with fatalities
2018	I	1.9	-0.3	17.8	10.0	84.1	5.5	32.7	99	1	0	2	0
	II	1.5	-1.4	9.4	1.0	81.7	4.1	74.6	101	0	0	0	0
	III	5.5	1.0	28.4	5.0	71.9	4.8	155.2	87	3	1	2	0
	IV	8.7	3.1	26.5	0.0	65.1	4.7	185.9	106	5	3	2	0
	V	13.2	7.6	22.4	0.0	66.1	3.7	229.9	96	1	0	1	0
	VI	17.1	11.2	26.0	0.0	64.2	3.6	231.4	122	4	1	3	0
	VII	20.1	14.0	71.0	0.0	*61.4*	*4.0*	270.4	91	6	2	5	0
	VIII	22.5	15.5	19.1	0.0	53.2	4.4	329.3	92	5	3	4	0
	IX	*15.8*	*10.7*	28.8	0.0	*71.1*	*3.9*	*144.6*	119	3	2	1	0
	X	8.0	3.8	39.4	0.0	79.4	4.5	*82.4*	145	17	11	7	0
	XI	6.1	3.4	47.9	3.0	85.6	3.7	48.9	99	9	8	2	1
	XII	5.6	3.2	14.1	0.0	84.3	3.8	53.7	117	5	3	2	0
2019	I	-2.5	-5.0	16.1	6.0	85.8	3.6	45.6	106	9	5	4	1
	II	3.8	1.2	24.4	12.0	83.3	3.9	64.3	97	8	7	2	1
	III	4.5	1.3	31.5	6.0	81.6	3.2	106.4	101	11	7	3	2
	IV	9.5	4.5	11.3	0.0	66.7	3.1	191.0	122	12	12	3	0
	V	15.8	9.6	28.6	0.0	65.0	3.2	280.2	93	5	5	0	0
	VI	18.8	12.6	51.3	0.0	65.8	2.9	296.2	114	11	13	2	0
	VII	19.8	14.4	72.1	0.0	69.6	*2.7*	218.7	84	7	7	2	0
	VIII	18.9	13.2	23.0	0.0	69.0	2.6	246.5	98	15	12	4	0
	IX	17.2	10.9	7.7	0.0	65.0	2.9	245.1	88	7	7	1	0
	X	8.0	5.6	102.1	0.0	88.6	3.7	51.9	122	11	10	3	0
	XI	3.5	1.0	34.2	0.0	89.3	3.3	52.7	103	11	7	5	0
	XII	1.7	-0.5	37.4	9.0	89.3	3.6	58.3	112	8	7	2	0
2020	I	-3.0	-5.5	8.8	21.0	84.9	3.1	72.0	102	9	6	3	0

	II	0.1	-2.6	22.6	24.0	82.6	4.1	60.1	93	7	8	3	0
	III	7.0	3.1	22.1	4.0	73.3	3.4	133.3	63	2	2	0	0
	IV	8.3	4.0	37.7	0.0	73.6	3.7	139.3	66	2	1	1	0
	V	14.1	9.0	40.4	0.0	72.6	3.3	261.2	78	6	4	2	0
	VI	18.2	12.7	84.6	0.0	70.4	3.4	241.1	73	5	4	1	0
	VII	18.7	13.6	83.2	0.0	75.0	2.6	231.1	77	6	4	2	0
	VIII	20.0	14.5	46.5	0.0	72.2	2.7	251.2	93	16	10	7	0
	IX	14.3	10.6	104.6	0.0	85.1	3.3	115.7	106	12	9	3	1
	X	10.9	7.6	79.5	0.0	*84.8*	3.7	102.7	96	9	6	2	1
	XI	5.3	3.2	28.2	13.0	88.7	3.3	*26.5*	88	5	4	2	0
	XII	2.4	0.1	31.9	21.0	86.4	4.1	*31.7*	105	7	3	3	1
2021	I	1.2	-1.4	23.1	15.0	84.2	4.3	38.1	74	6	3	3	0
	II	-2.7	-6.0	2.9	2.0	78.0	2.8	97.4	78	4	4	0	2
	III	1.1	-2.8	19.7	2.0	71.3	3.8	141.9	72	5	4	3	0
	IV	13.4	7.3	20.0	0.0	66.6	3.9	251.0	62	2	1	1	0
	V	17.0	11.0	44.5	0.0	65.4	3.2	331.9	102	14	11	6	0
	VI	18.7	12.8	42.1	0.0	67.0	2.9	232.6	86	10	9	2	0
	VII	20.7	15.1	87.7	0.0	70.3	2.6	197.9	98	10	12	1	0
	VIII	21.4	15.3	26.5	0.0	65.5	2.6	293.6	101	6	3	3	0
	IX	16.7	11.1	30.8	0.0	69.0	2.9	232.6	120	11	5	6	0
	X	11.1	6.2	44.0	0.0	76.7	3.5	164.3	110	11	6	6	0
	XI	5.2	2.6	7.6	0.0	86.2	3.6	24.8	87	3	3	3	0
	XII	2.1	0.2	31.9	1.0	88.7	3.7	23.1	95	7	3	4	0
2022	I	-1.0	-3.1	26.1	4.0	86.1	3.9	23.2	101	2	5	0	0
	II	3.5	-0.2	25.2	10.0	78.8	3.7	125.1	55	1	2	0	0
	III	6.9	2.8	35.4	0.0	73.9	4.1	144.5	88	8	8	1	0
	IV	10.2	3.8	14.6	0.0	57.6	4.2	282.9	90	8	6	2	0
	V	12.8	7.9	44.7	0.0	72.6	3.1	191.3	81	8	9	1	0
	VI	22.1	15.1	23.7	0.0	63.5	3.1	334.1	67	4	3	1	0
	VII	19.5	13.8	50.7	0.0	64.4	3.1	221.0	75	4	5	0	0
	VIII	20.8	15.0	44.7	0.0	67.2	2.7	268.8	86	7	9	0	0
	IX	15.0	10.1	58.9	0.0	77.2	3.2	165.6	77	7	10	3	0
	X	11.5	7.2	15.2	2.0	82.6	2.8	141.9	77	5	5	1	0
	XI	6.3	3.3	15.1	0.0	87.8	4.0	55.0	53	3	1	2	0
	XII	3.6	1.2	13.9	7.0	84.4	3.5	38.3	83	2	1	1	0
2023	I	2.9	0.4	20.8	16.0	85.9	3.6	58.7	62	7	8	3	0
	II	4.7	1.7	56.8	15.0	78.1	4.4	52.8	61	3	2	1	0
	III	5.4	0.7	23.1	15.0	65.0	3.9	196.6	96	5	5	0	0
	IV	9.2	2.0	4.2	28.0	52.6	3.3	298.9	87	6	6	3	1
	V	11.7	6.0	68.2	0.0	67.4	3.1	215.5	83	11	9	4	0
	VI	18.5	13.6	122.2	0.0	77.8	2.8	197.7	79	9	10	1	0
	VII	19.1	13.1	28.0	0.0	67.9	2.7	246.6	72	3	3	0	0
	VIII	20.7	14.9	70.7	0.0	66.3	2.9	267.1	86	15	17	2	0
	IX	*16.4*	*11.2*	88.1	0.0	*78.9*	*2.7*	*168.4*	80	8	7	2	0
	X	11.1	8.0	79.4	0.0	86.3	2.8	101.1	84	7	7	2	0
	XI	6.1	3.9	11.0	1.0	88.9	2.9	48.4	93	9	5	4	0
	XII	2.4	0.3	17.9	2.0	87.9	4.2	27.7	80	12	10	4	0
2024	I	0.9	-2.7	24.8	4.0	85.8	4.0	47.5	71	2	1	1	0
	II	1.8	-1.2	22.9	3.0	80.4	3.8	83.9	59	5	5	1	0
	III	5.0	1.1	26.7	0.0	73.3	3.9	154.1	73	4	4	1	0
	IV	11.4	6.5	37.2	0.0	71.7	3.7	186.2	74	7	11	1	0
	V	16.6	10.0	16.1	0.0	62.2	3.0	313.0	84	3	3	0	0
	VI	19.0	13.5	74.6	0.0	*72.2*	2.7	254.3	81	6	9	0	0
	VII	20.9	15.0	124.0	0.0	*69.9*	2.8	305.2	91	5	5	1	0
	VIII	20.6	14.7	45.0	0.0	*68.6*	2.5	280.6	72	7	5	1	1
	IX	17.6	12.0	60.8	0.0	*65.1*	3.6	237.4	94	8	3	5	0
	X	10.9	7.0	32.4	0.0	*79.2*	3.4	158.9	100	13	8	5	1
	XI	4.4	2.3	31.3	0.0	*84.0*	3.8	42.4	85	4	2	2	0
	XII	3.3	1.5	21.3	1.0	*88.3*	3.9	30.1	102	6	6	1	0

Table 3 Statistic data for Leszno [20,21]

Year	Month	Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine	Number of incidents	Number of accidents	Number of accidents with minor injuries	Number of accidents with serious injuries	Number of accidents with fatalities
2018	I	2.5	0.5	44.8	*3.0*	81.5	3.9	37.4	85	7	5	2	1
	II	-2.4	-5.4	2.0	*1.0*	76.6	2.9	135.0	82	5	5	0	0
	III	0.9	-3.1	24.8	*0.0*	73.0	3.6	136.0	89	8	9	0	0
	IV	13.1	6.3	10.2	*0.0*	67.2	3.6	277.1	85	7	6	3	0
	V	16.7	9.4	25.6	*0.0*	64.6	3.2	328.7	109	10	6	4	0
	VI	18.7	12.3	40.0	*0.0*	64.5	3.4	236.2	96	5	5	0	0
	VII	20.3	14.0	86.1	*0.0*	67.2	3.1	293.7	83	12	8	4	0
	VIII	21.3	14.6	13.9	*0.0*	61.3	2.5	285.4	72	7	8	1	0
	IX	15.7	10.4	74.1	*0.0*	71.6	2.8	228.0	98	8	6	3	0
	X	10.7	5.4	35.9	*0.0*	75.8	3.3	173.3	107	15	11	7	0
	XI	5.1	2.2	15.1	*0.0*	85.9	2.9	92.2	84	12	7	5	1

	XII	3.0	0.9	41.4	*0.0*	88.9	4.0	20.0	98	10	7	3	0
2019	I	-0.1	-2.5	42.8	2.0	87.4	4.3	35.7	90	7	3	4	0
	II	3.2	-0.8	10.7	2.0	78.3	3.7	133.4	66	7	11	1	0
	III	6.4	2.2	36.9	0.0	75.8	4.2	131.3	91	7	5	2	0
	IV	10.4	3.8	8.6	0.0	59.4	3.9	270.2	93	10	7	3	0
	V	11.8	6.1	91.7	0.0	74.3	3.2	224.2	75	14	14	2	0
	VI	22.2	14.7	8.8	0.0	60.6	3.1	373.7	95	17	8	12	1
	VII	19.1	12.8	56.5	0.0	65.1	3.2	233.2	84	15	14	5	0
	VIII	20.6	14.4	43.7	0.0	67.0	2.4	266.2	85	6	5	1	0
	IX	14.4	9.5	83.6	0.0	75.5	3.0	180.2	92	11	7	4	0
	X	10.7	6.3	20.9	0.0	82.5	2.6	151.3	116	11	15	2	0
	XI	6.8	3.9	49.4	0.0	85.1	3.1	93.4	90	8	4	5	0
	XII	3.6	0.6	14.3	0.0	82.9	3.4	53.8	85	13	11	2	1
2020	I	2.9	-0.4	20.5	0.0	84.3	3.7	76.2	95	9	4	6	0
	II	5.1	2.1	63.0	0.0	77.9	5.0	79.1	70	8	7	1	0
	III	5.0	0.2	20.4	1.0	66.8	3.8	208.2	61	1	1	0	0
	IV	9.3	1.1	5.7	0.0	54.4	3.3	310.5	25	1	1	0	0
	V	11.8	5.4	45.9	0.0	67.0	3.5	250.7	60	6	3	3	0
	VI	17.9	12.8	52.6	0.0	76.6	3.2	224.3	76	10	11	3	0
	VII	18.8	12.1	31.9	0.0	65.7	2.8	270.7	55	7	7	0	0
	VIII	20.6	14.7	86.4	0.0	68.6	2.8	250.2	72	5	6	1	0
	IX	15.3	9.2	37.9	0.0	76.8	2.5	217.4	72	9	7	2	0
	X	11.0	8.0	87.4	*0.0*	84.3	2.9	85.0	72	3	3	0	0
	XI	6.0	3.1	15.2	*0.0*	87.4	2.7	68.3	49	1	1	0	0
	XII	2.6	0.1	13.7	*4.0*	85.2	3.1	78.7	81	11	10	3	0
2021	I	-0.2	-2.1	24.6	*8.0*	87.5	3.2	40.8	49	3	3	1	0
	II	-0.4	-4.5	15.7	*9.0*	80.7	3.4	100.8	51	1	1	0	0
	III	4.1	-0.1	15.1	0.0	74.6	3.3	157.3	58	9	9	2	0
	IV	6.4	1.9	32.3	0.0	70.8	3.8	158.0	56	7	7	2	0
	V	12.2	7.2	69.4	*0.0*	71.5	3.5	210.5	74	7	7	2	2
	VI	19.8	12.7	59.5	*0.0*	65.6	2.6	310.6	82	3	4	0	0
	VII	20.4	15.0	72.2	*0.0*	73.1	2.6	220.9	59	4	4	1	0
	VIII	17.4	12.7	126.7	*0.0*	75.6	2.6	185.7	81	7	5	3	0
	IX	15.3	10.7	19.1	*0.0*	77.8	2.6	189.6	89	6	4	2	0
	X	10.0	5.0	20.6	*0.0*	77.3	2.9	167.2	96	8	6	3	0
	XI	5.5	3.1	29.4	*0.0*	88.6	3.4	47.8	63	2	1	1	0
	XII	0.5	-2.0	36.1	*8.0*	89.2	3.4	49.9	75	4	4	0	0
2022	I	2.1	-0.1	29.6	*3.0*	86.1	4.7	63.4	46	3	2	1	0
	II	4.4	1.4	48.7	*1.0*	78.1	5.2	87.1	53	1	0	1	0
	III	4.0	-2.2	0.0	*0.0*	60.4	3.0	254.7	67	7	7	0	0
	IV	7.6	2.4	34.2	*0.0*	67.5	3.8	189.8	59	3	4	0	0
	V	14.6	7.6	51.3	*0.0*	62.9	3.1	281.3	51	2	2	0	0
	VI	19.5	12.2	39.4	*0.0*	64.1	2.8	295.9	66	6	3	2	1
	VII	19.9	13.1	45.7	*0.0*	59.6	3.4	286.8	48	0	0	0	0
	VIII	21.3	15.6	89.1	*0.0*	69.2	2.7	245.6	52	5	2	3	0
	IX	13.3	8.7	50.6	*0.0*	77.0	2.6	189.0	61	8	8	0	0
	X	11.7	7.0	44.9	*0.0*	84.5	2.5	170.8	44	2	1	1	0
	XI	4.8	1.7	10.4	*0.0*	87.8	2.6	70.0	49	2	2	0	0
	XII	1.5	-0.8	28.1	*0.0*	86.5	3.3	32.7	60	11	10	3	0
2023	I	3.4	1.2	37.8	*2.0*	86.1	3.6	35.5	56	3	0	5	0
	II	2.5	-0.5	43.8	*1.0*	80.3	4.1	87.0	44	3	2	1	0
	III	5.0	1.0	36.0	*5.0*	77.4	3.8	101.1	55	1	1	0	0
	IV	7.7	3.1	31.2	*0.0*	75.8	3.2	145.5	62	7	8	0	0
	V	13.2	6.9	23.8	*0.0*	64.1	3.3	295.5	58	9	8	2	0
	VI	18.3	11.0	62.6	*0.0*	64.0	2.7	275.7	44	2	1	1	0
	VII	20.1	12.9	36.4	*0.0*	62.4	2.9	283.8	55	8	7	6	0
	VIII	19.7	15.0	145.9	*0.0*	75.7	2.6	222.9	43	4	3	1	0
	IX	17.9	11.4	11.6	*0.0*	74.4	2.2	284.7	69	6	3	3	0
	X	11.5	7.8	101.3	*0.0*	84.4	2.9	89.3	65	9	10	1	0
	XI	5.2	2.6	70.2	*3.0*	85.0	3.5	76.9	63	4	2	2	0
	XII	2.9	0.6	70.9	*7.0*	86.9	4.1	33.7	74	8	4	4	0
2024	I	0.7	-2.2	29.4	*4.0*	81.6	4.4	74.8	65	4	4	1	0
	II	6.7	4.0	79.6	*0.0*	85.7	4.0	47.0	49	1	0	1	0
	III	8.2	3.9	12.6	*0.0*	75.2	3.1	140.7	65	5	5	1	0
	IV	11.3	5.9	24.6	*0.0*	70.1	3.2	184.9	54	3	2	1	0
	V	17.2	10.9	35.0	*0.0*	63.2	2.8	300.7	61	8	6	2	0
	VI	18.8	13.2	93.7	*0.0*	72.1	2.7	237.0	57	7	8	1	0
	VII	20.3	14.6	86.2	*0.0*	73.2	2.6	283.9	66	7	4	3	1
	VIII	20.7	15.0	150.1	*0.0*	72.4	2.4	286.9	68	5	2	3	0
	IX	16.9	12.3	69.7	*0.0*	74.5	3.5	221.0	62	10	10	4	0
	X	11.2	7.5	16.9	*0.0*	83.5	2.9	142.1	80	7	5	3	0
	XI	4.4	2.1	29.8	*3.0*	91.5	3.3	35.9	57	4	2	3	0
	XII	2.8	0.7	14.9	*0.0*	90.7	3.3	41.8	64	5	6	1	0

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Table 4 Statistic data for Poznan [20,21]

Year	Month	Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine	Number of incidents	Number of accidents	Number of accidents with minor injuries	Number of accidents with serious injuries	Number of accidents with fatalities
2018	I	2.2	0.1	48.7	4.0	84.6	4.7	41.7	733	49	45	9	3
	II	-2.6	-5.5	4.4	1.0	78.9	3.3	101.1	652	51	50	10	0
	III	1.0	-2.8	29.4	1.0	72.1	4.3	121.2	781	73	59	26	2
	IV	13.4	7.6	28.1	0.0	64.7	4.3	272.7	813	69	59	18	2
	V	17.9	11.2	16.6	0.0	55.9	3.9	350.4	801	85	75	26	1
	VI	19.4	13.9	22.8	0.0	58.1	4.0	271.8	725	87	67	30	3
	VII	20.9	14.9	81.3	0.0	63.7	3.5	310.2	662	86	67	26	2
	VIII	21.7	15.9	9.8	0.0	57.2	3.3	313.1	662	64	61	15	1
	IX	16.1	11.3	40.7	0.0	67.3	3.4	205.9	799	83	64	27	4
	X	10.9	6.3	23.4	0.0	73.6	4.1	161.1	937	86	74	18	2
	XI	5.2	2.7	7.8	0.0	84.3	3.7	60.1	709	62	57	17	4
	XII	2.8	0.8	59.5	2.0	88.4	4.5	15.5	814	67	68	25	2
2019	I	-0.2	-2.4	58.7	3.0	88.2	4.6	31.8	770	58	48	19	3
	II	3.4	0.0	15.9	2.0	77.2	4.2	107.8	743	57	61	8	0
	III	6.4	3.0	39.8	0.0	73.8	4.8	119.4	797	61	47	27	0
	IV	10.9	4.6	7.2	0.0	52.6	4.6	277.7	801	70	55	24	0
	V	12.4	7.4	83.5	0.0	69.7	3.8	208.6	774	71	58	17	3
	VI	23.3	16.6	3.4	0.0	55.5	3.6	378.8	724	72	57	23	1
	VII	19.7	14.3	22.8	0.0	61.7	3.9	248.4	671	88	84	17	0
	VIII	21.2	15.6	32.4	0.0	63.5	3.1	289.9	705	109	101	21	2
	IX	14.6	10.5	40.1	0.0	75.3	3.8	159.4	752	97	88	23	1
	X	10.9	7.0	19.2	0.0	83.6	3.1	114.4	948	111	105	22	0
	XI	6.6	4.3	46.2	0.0	88.4	4.0	63.2	782	74	48	30	2
	XII	3.7	1.4	23.6	0.0	85.9	3.8	40.7	691	64	53	16	1
2020	I	3.3	1.1	37.4	0.0	87.8	4.1	67.3	705	60	43	23	3
	II	5.0	2.3	76.3	0.0	79.5	5.1	65.4	718	67	70	17	1
	III	5.2	1.0	29.0	0.0	65.7	4.2	*120.3*	491	36	28	8	1
	IV	9.8	2.7	2.6	0.0	50.2	3.9	234.8	361	27	25	6	3
	V	12.0	6.6	47.5	0.0	63.1	4.1	*279.5*	528	44	32	13	2
	VI	18.5	13.8	51.3	0.0	70.8	3.7	225.6	626	60	57	12	0
	VII	19.3	14.0	65.3	0.0	61.6	3.6	286.4	661	61	52	15	1
	VIII	21.0	15.7	60.9	0.0	63.4	3.3	265.1	668	62	43	28	0
	IX	15.6	10.2	37.4	0.0	73.5	2.9	189.3	719	80	66	20	1
	X	11.0	8.3	41.0	0.0	83.4	3.4	81.9	622	57	51	18	0
	XI	6.2	4.0	11.8	0.0	88.6	3.3	46.7	512	35	32	8	1
	XII	2.4	0.3	31.5	2.0	88.1	4.0	34.5	611	30	21	13	2
2021	I	-0.5	-2.2	53.5	12.0	91.1	3.5	30.5	527	32	27	10	0
	II	-0.4	-4.1	35.0	6.0	83.6	3.7	96.2	582	31	27	10	1
	III	4.1	-0.2	22.1	1.0	75.6	3.5	142.7	714	32	21	13	1
	IV	6.6	2.2	33.7	1.0	69.4	4.2	149.0	592	31	25	14	2
	V	12.6	7.9	62.6	0.0	69.9	4.1	188.2	716	44	34	17	0
	VI	20.7	14.4	92.8	0.0	58.9	3.2	264.9	708	47	35	18	2
	VII	21.2	16.4	32.3	0.0	68.6	3.4	198.0	575	33	27	8	1
	VIII	17.9	13.4	81.7	0.0	70.7	3.4	157.8	585	37	34	16	3
	IX	15.5	11.2	13.8	0.0	74.8	3.4	154.4	660	48	34	18	1
	X	10.3	6.1	25.0	0.0	76.7	3.6	153.2	727	49	31	26	1
	XI	5.7	3.8	38.1	0.0	89.8	4.0	34.4	649	49	44	8	1
	XII	0.0	-2.5	36.5	8.0	91.1	4.1	43.4	654	37	33	11	1
2022	I	1.7	-0.5	46.1	4.0	89.0	5.0	50.6	542	30	23	8	1
	II	4.3	1.7	57.2	0.0	78.3	5.5	83.9	579	33	25	10	3
	III	4.3	-1.4	2.1	0.0	57.0	3.4	229.2	642	35	28	12	0
	IV	7.9	2.7	36.3	0.0	63.3	4.3	168.8	588	37	32	10	0
	V	14.9	8.7	22.6	0.0	57.1	3.9	233.1	652	54	41	20	0
	VI	19.9	13.5	63.4	0.0	60.5	3.5	244.6	605	77	63	31	5
	VII	20.2	14.7	22.7	0.0	59.2	4.1	238.9	552	56	36	28	1
	VIII	22.1	16.6	52.8	0.0	64.4	3.3	222.3	561	53	35	21	4
	IX	13.4	9.0	31.6	0.0	73.6	3.3	171.6	551	43	35	14	1
	X	12.0	7.9	28.3	0.0	83.6	3.0	149.9	636	68	60	17	1
	XI	4.8	2.6	16.3	6.0	89.7	3.4	54.1	638	29	24	10	1
	XII	1.3	-0.8	35.2	1.0	89.4	3.8	27.3	609	37	26	16	1
2023	I	3.4	1.5	53.3	6.0	89.1	3.8	27.3	571	35	32	10	1
	II	2.2	-0.8	40.1	0.0	82.1	4.5	82.2	540	39	29	14	1
	III	4.8	1.2	51.4	1.0	79.2	4.0	89.9	602	24	17	7	0
	IV	8.4	4.0	36.8	0.0	72.3	3.7	148.8	582	41	37	7	1
	V	13.8	7.6	29.5	0.0	58.9	3.9	308.2	613	54	40	15	0
	VI	19.4	13.2	38.7	0.0	56.7	3.3	287.0	603	55	44	19	0
	VII	20.5	14.3	61.7	0.0	56.8	3.5	280.2	568	47	34	14	0
	VIII	19.8	15.2	156.1	0.0	70.7	3.1	219.9	576	59	46	23	0
	IX	18.6	12.6	3.3	0.0	68.6	2.8	292.8	640	54	42	14	0
	X	11.1	7.5	78.4	0.0	82.6	3.6	75.1	744	37	31	15	1
	XI	4.7	1.6	84.5	4.0	85.6	3.8	67.6	721	39	28	14	3

	XII	2.7	0.5	76.7	5.0	86.1	4.7	35.9	749	50	39	13	2
2024	I	0.5	-2.1	48.9	6.0	82.3	4.7	64.0	737	36	24	16	0
	II	6.3	3.8	74.4	0.0	85.8	4.4	34.3	787	32	23	10	0
	III	7.7	3.7	20.0	0.0	76.2	3.8	136.9	755	44	38	11	0
	IV	11.3	6.1	49.5	0.0	68.9	3.7	172.2	808	40	31	13	2
	V	17.3	11.1	52.2	0.0	60.0	3.7	303.0	727	53	41	15	0
	VI	18.8	13.8	97.1	0.0	68.6	3.4	241.8	725	60	41	24	0
	VII	20.6	15.2	75.3	0.0	66.9	3.1	272.5	693	77	61	24	5
	VIII	21.3	15.5	38.8	0.0	63.2	3.2	286.2	655	56	36	25	0
	IX	17.5	12.8	56.3	0.0	67.8	4.1	210.6	692	56	45	14	1
	X	10.9	7.2	20.0	0.0	80.4	3.5	138.5	772	62	55	14	2
	XI	4.4	2.5	31.9	0.0	88.1	3.6	26.1	634	41	33	13	0
	XII	3.3	1.6	18.0	0.0	90.0	3.8	27.5	689	45	42	11	1

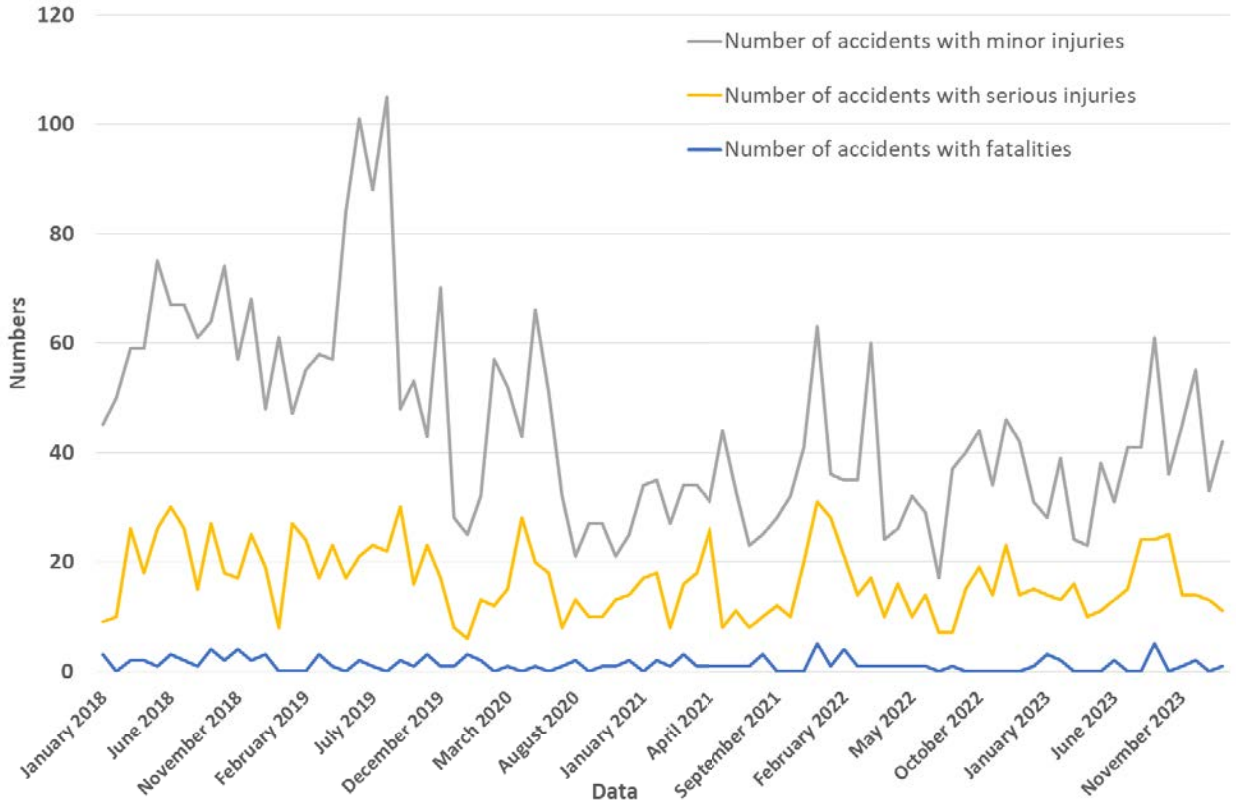


Figure 1 Statistic data for Poznan [20,21]

Table 5 Statistic data for Kalisz [20,21]

Year	Month	Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine	Number of incidents	Number of accidents	Number of accidents with minor injuries	Number of accidents with serious injuries	Number of accidents with fatalities
2018	I	1.8	-0.2	24.7	7.0	87.1	4.6	40.5	161	2	1	1	1
	II	-2.7	-4.9	1.8	1.0	83.6	3.1	116.4	125	5	3	3	0
	III	1.0	-2.4	29.8	4.0	77.3	3.9	125.7	142	3	0	2	1
	IV	13.8	8.3	18.7	1.0	68.6	4.0	258.3	143	6	2	7	2
	V	17.4	11.7	51.2	0.0	67.3	3.3	332.6	145	3	1	2	0
	VI	18.7	13.5	34.0	0.0	69.3	3.2	230.5	153	10	2	8	0
	VII	20.6	14.8	45.1	0.0	70.9	2.8	273.8	147	7	3	3	1
	VIII	21.5	16.0	33.1	0.0	65.5	2.8	270.6	135	7	2	5	1
	IX	16.4	11.4	39.6	0.0	70.8	3.4	209.7	160	15	14	3	0
	X	11.1	6.9	38.5	0.0	78.2	4.0	148.6	185	21	21	3	0
	XI	5.4	3.1	6.4	0.0	87.5	3.3	84.4	138	6	3	5	0
	XII	2.2	0.4	41.1	1.0	93.4	4.3	26.2	138	5	2	2	1
2019	I	-0.8	-2.9	37.8	4.0	90.0	4.4	33.4	154	12	10	4	2
	II	3.1	0.0	26.2	11.0	77.9	4.1	129.2	147	7	7	3	0
	III	6.2	2.7	28.7	0.0	77.8	4.9	120.3	179	14	11	4	1
	IV	10.5	4.7	19.8	0.0	60.4	3.9	240.6	154	22	22	5	0
	V	12.2	7.6	47.7	0.0	76.7	3.4	187.1	143	12	10	4	0

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	VI	22.6	16.3	24.2	0.0	62.2	3.1	345.6	144	11	7	3	1
	VII	19.4	14.0	28.9	0.0	64.9	3.0	205.5	150	18	7	12	1
	VIII	21.0	15.7	37.4	0.0	66.6	3.0	242.6	118	7	8	3	0
	IX	14.7	10.5	50.3	0.0	77.9	3.6	162.6	149	11	13	2	0
	X	11.2	7.3	17.0	0.0	83.3	3.4	150.6	186	20	16	5	0
	XI	6.6	3.8	23.2	0.0	89.6	3.8	58.9	129	12	11	4	0
	XII	3.6	1.5	14.9	0.0	87.4	4.0	52.7	150	3	4	1	0
2020	I	2.5	0.4	24.6	0.0	89.8	4.2	71.9	158	11	7	2	4
	II	4.4	1.9	58.2	0.0	81.9	5.5	66.5	154	8	4	6	0
	III	5.0	1.0	20.7	2.0	68.3	4.3	186.5	113	4	1	2	1
	IV	9.7	3.1	4.5	0.0	53.4	3.6	283.2	75	2	0	2	0
	V	11.7	6.7	73.1	0.0	71.2	3.5	227.1	96	7	4	3	0
	VI	18.1	13.8	79.2	0.0	79.1	3.3	274.3	111	10	4	9	0
	VII	18.9	13.4	41.6	0.0	68.8	2.8	*173.1*	106	3	0	3	0
	VIII	20.5	15.4	92.9	0.0	69.8	2.9	255.2	103	7	3	6	0
	IX	15.7	11.1	70.6	0.0	78.0	2.9	202.9	141	5	2	2	1
	X	10.8	8.4	90.2	0.0	88.4	3.3	85.9	145	7	3	5	0
	XI	5.9	3.8	17.5	0.0	92.5	3.3	54.3	97	3	1	2	0
	XII	2.2	0.5	19.1	1.0	91.6	3.7	51.1	139	3	2	2	0
2021	I	-0.9	-2.7	28.2	13.0	92.8	3.2	35.2	114	3	1	4	2
	II	-0.8	-3.9	19.8	10.0	86.5	2.8	82.8	142	3	1	2	0
	III	4.2	0.9	12.6	0.0	77.8	3.0	137.4	149	4	0	5	0
	IV	6.5	2.5	36.4	0.0	72.5	4.1	148.9	124	1	0	1	0
	V	12.4	7.9	80.7	0.0	73.6	4.1	194.7	159	8	4	5	0
	VI	20.2	14.5	31.4	0.0	64.9	2.7	324.4	142	4	3	2	0
	VII	21.1	16.2	102.4	0.0	73.3	2.8	199.8	128	7	4	3	0
	VIII	17.3	13.4	122.6	0.0	77.9	3.2	157.2	138	3	0	3	0
	IX	15.1	10.9	8.1	0.0	77.2	3.2	*149.4*	123	3	1	2	0
	X	10.3	6.2	12.7	0.0	75.4	4.0	128.4	173	5	2	5	0
	XI	5.3	3.5	32.0	4.0	89.3	4.2	61.5	138	6	0	6	0
	XII	-0.4	-2.6	26.5	7.0	91.1	3.8	32.1	129	3	2	1	0
2022	I	1.3	-0.6	27.3	6.0	88.0	5.3	41.6	96	3	2	1	0
	II	3.7	1.2	34.6	0.0	80.0	5.9	*66.5*	112	2	0	2	0
	III	4.3	-0.5	0.2	0.0	59.0	3.3	241.0	118	3	1	2	0
	IV	7.6	3.2	30.8	0.0	66.3	4.5	160.4	129	1	1	0	0
	V	14.7	9.0	36.9	0.0	60.8	3.4	276.0	116	5	2	1	2
	VI	19.8	14.0	55.1	0.0	65.7	2.9	295.9	123	8	4	5	0
	VII	19.6	14.2	88.4	0.0	66.2	3.1	253.7	117	1	0	1	0
	VIII	21.1	16.1	61.4	0.0	73.5	2.7	248.5	90	5	0	4	1
	IX	12.9	8.7	50.6	0.0	79.5	3.0	173.0	113	3	0	3	0
	X	12.1	8.2	19.0	0.0	84.5	3.1	152.4	117	3	2	2	0
	XI	4.4	2.1	8.8	0.0	90.1	2.9	63.1	127	3	0	3	0
	XII	1.1	-0.9	24.1	8.0	92.7	4.0	20.3	108	4	4	1	0
2023	I	3.3	1.7	26.7	5.0	91.5	4.1	43.7	111	1	2	0	0
	II	1.9	-0.3	27.1	1.0	87.8	4.5	57.3	89	3	2	2	0
	III	4.9	1.5	28.0	2.0	81.6	4.2	85.7	118	4	0	4	0
	IV	8.1	4.3	27.1	0.0	*75.8*	3.5	128.2	117	4	0	4	0
	V	13.5	8.3	31.1	0.0	*60.8*	3.4	277.9	112	2	1	1	0
	VI	18.8	13.0	30.5	0.0	*61.7*	3.0	277.1	123	9	2	6	1
	VII	20.9	14.9	47.9	0.0	59.0	3.2	250.2	116	3	0	3	0
	VIII	20.2	15.9	59.7	0.0	72.8	3.3	212.8	91	4	0	4	0
	IX	19.1	13.6	18.9	0.0	68.8	2.8	261.5	120	6	1	6	0
	X	11.4	8.0	55.3	0.0	85.5	3.8	80.7	151	3	1	2	0
	XI	4.7	2.3	64.0	0.0	87.6	4.1	59.5	123	6	2	4	0
	XII	2.4	0.5	43.0	7.0	88.9	4.9	26.0	137	4	1	2	1
2024	I	0.4	-1.8	27.4	3.0	84.5	5.1	60.4	109	3	0	3	0
	II	6.5	4.1	51.4	4.0	86.4	4.6	48.6	97	2	0	2	0
	III	8.0	4.4	12.4	0.0	77.3	3.7	128.1	141	9	1	9	0
	IV	11.7	7.2	24.3	0.0	69.4	3.9	161.0	134	6	1	5	0
	V	17.1	11.1	31.6	0.0	62.6	2.9	293.8	131	2	0	2	1
	VI	19.1	14.4	88.5	0.0	73.4	2.9	240.8	116	5	0	5	0
	VII	20.9	15.5	93.5	0.0	70.9	2.7	269.5	117	8	2	6	0
	VIII	20.8	15.9	138.0	0.0	71.9	2.6	261.1	130	8	3	5	0
	IX	17.4	12.7	79.7	0.0	72.5	3.8	214.4	139	6	3	3	1
	X	11.0	7.4	22.6	0.0	83.8	3.3	143.4	166	6	0	6	0
	XI	4.0	2.0	27.8	0.0	*89.8*	3.8	41.5	139	5	1	2	2
	XII	3.0	1.4	15.7	0.0	92.4	4.0	43.1	130	2	0	2	0

Descriptive statistics were computed for the monthly number of road accidents in each city, including the mean, standard deviation, minimum, and maximum values. These metrics provide a summary of typical accident frequency, variability, and extreme monthly values, facilitating comparative assessment between cities of different sizes and traffic densities.

Neural network models were applied to forecast monthly road accidents over 6- and 12-month horizons. The input features included historical accident counts, temporal variables (month, year), and meteorological variables. Multilayer perceptron (MLP) networks were selected due to their ability to capture nonlinear relationships between predictor

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variables and accident occurrence. The models were trained on the historical data using a rolling forecast approach, ensuring that each prediction relied only on past information.

Multilayer perceptron (MLP) models were implemented for each city separately. The architecture consisted of an input layer with 10–15 features (lagged accident counts up to 12 months, month index, year, mean temperature, total precipitation, sunshine duration, etc.), one or two hidden layers with 8–32 neurons each (selected via grid search), and a single output neuron predicting the number of accidents in the target month. ReLU activation was used in hidden layers and linear activation in the output layer. A rolling-window approach was applied: the model was trained on all data up to time t and used to forecast t+1 to t+12, then the window was shifted forward.

Data were normalized using min-max scaling. No explicit train/validation/test split was used due to the time-series nature; instead, forecasts were generated in a true out-of-sample manner. Hyperparameters (number of neurons, layers, learning rate) were tuned separately for each city using a grid search over 5-fold time-series cross-validation on the training portion.

Forecast performance was assessed using three standard error metrics: Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and Mean Absolute Percentage Error (MAPE). MAE and RMSE quantify absolute forecast deviations, while MAPE expresses errors relative to observed values, providing insight into relative accuracy, especially for cities with low accident baselines (1), (2), (3), (4). The analysis compared forecast errors between the 6- and 12-month horizons to evaluate the impact of extending the prediction period on accuracy.

- ME – mean error

$$ME = \frac{1}{n}\sum_{i=1}^{n}(Y_i - Y_p), \tag{1}$$

- MAE – mean absolute error

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|Y_i - Y_p|, \tag{2}$$

- MPE – mean percentage error

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\frac{Y_i - Y_p}{Y_i}, \tag{3}$$

- MAPE - mean absolute percentage error

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{|Y_i - Y_p|}{Y_i}, \tag{4}$$

where:
n - length of the forecast horizon,
Y - observed value of traffic accidents,
Y_p - the forecast value of traffic accidents.

4 Results

Table 5 presents descriptive statistics for the monthly number of road accidents in the five analyzed cities over 2018–2024. Poznań exhibits the highest average monthly accident count (mean ≈ 54.4) and the greatest variability (standard deviation ≈ 19.1), reflecting its larger population and traffic volume. In contrast, Piła shows the lowest mean monthly accidents (≈ 1.4), with several months recording zero accidents, indicating sporadic accident occurrence. Konin, Leszno, and Kalisz have intermediate mean accident counts (≈ 6–7) with moderate variability. Maximum monthly accident counts range from 7 in Piła to 111 in Poznań, demonstrating occasional spikes in larger urban areas.

The descriptive statistics reveal clear differences in accident frequency across cities, consistent with population density and urban traffic conditions. Smaller cities exhibit lower baseline accident levels but proportionally higher variability relative to their mean, suggesting that single events can significantly affect relative accident statistics.

Table 5 Descriptive statistics of monthly road accidents (2018–2024)

City	Mean	Standard deviation	Minimum	Maximum
Piła	1.4	1.5	0	7
Konin	6.8	3.7	0	17
Leszno	6.5	3.6	0	17
Poznań	54.4	19.1	24	111
Kalisz	6.1	4.4	1	22

Table 6 summarizes forecast accuracy metrics for the 6-month-ahead predictions. Poznań's forecasts show the highest absolute errors (MAE ≈ 8.1, RMSE ≈ 9.5) due to the large number of accidents, yet relative errors (MAPE ≈ 17.7%) remain low, indicating robust predictive performance. Conversely, smaller cities such as Piła, Konin, and Kalisz exhibit

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high MAPE values (e.g., Konin ≈ 111.9%), reflecting substantial relative error caused by low accident counts, despite low absolute errors (MAE ≈ 0.9–3.3). Leszno demonstrates intermediate forecast accuracy (MAPE ≈ 43.8%). These results highlight the challenge of predicting rare events: even minor deviations lead to high percentage errors when accident baselines are low.

Table 6 Forecast accuracy measures for the 6-month horizon

City	MAE	RMSE	MAPE
Piła	0.9	1.2	57.7%
Konin	3.3	4.3	111.9%
Leszno	1.5	1.6	43.8%
Poznań	8.1	9.5	17.7%
Kalisz	2.6	3.1	65.5%

Extending the forecast horizon to 12 months generally increases prediction errors (Table 7). MAE and RMSE rise for most cities: for instance, Poznań's MAE increases from 8.1 to 10.1 and Piła's from 0.9 to 1.3. MAPE values also grow for most cities, particularly for Piła (≈ 89.6%), indicating reduced relative forecast accuracy over longer horizons. Notably, Konin and Kalisz display slight reductions in MAPE and RMSE at the 12-month horizon, suggesting that in these medium-sized cities, the 12-month forecast aligned better with actual outcomes than the 6-month forecast, possibly due to annual seasonal patterns captured by the model.

Table . Forecast accuracy measures for the 12-month horizon

City	MAE	RMSE	MAPE
Piła	1.3	1.6	89.6%
Konin	3.3	3.9	81.5%
Leszno	1.7	2.0	38.0%
Poznań	10.1	12.5	19.3%
Kalisz	2.5	2.9	61.7%

Table 8 shows the relative change in forecast accuracy when extending from a 6- to a 12-month horizon. Most cities experience higher MAE and RMSE (e.g., Piła +45.5% MAE, Poznań +32.1% RMSE), confirming the general trend of reduced accuracy for longer-term forecasts. However, Konin and Kalisz show negative Δ values, indicating minor improvements in forecast precision over the 12-month horizon. This anomaly suggests that short-term fluctuations can disproportionately affect 6-month forecasts, whereas the 12-month model benefits from capturing full-year patterns (Figure 2).

Table 8 Relative change in forecast accuracy between 6- and 12-month horizons

City	ΔMAE (%)	ΔRMSE (%)
Piła	+45.5%	+35.1%
Konin	–1.1%	–8.2%
Leszno	+19.8%	+23.0%
Poznań	+25.1%	+32.1%
Kalisz	–1.2%	–6.1%

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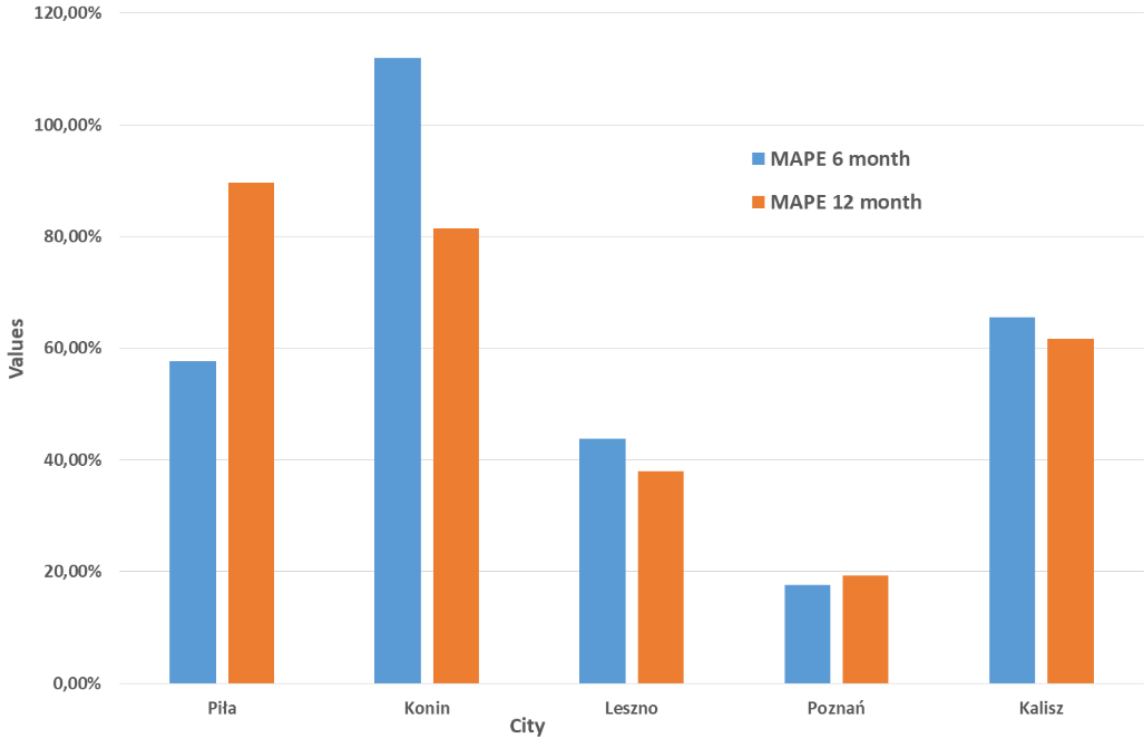


Figure 2 Mean Absolute Percentage Error (MAPE) for 6-month and 12-month forecast horizons across the five cities

Overall, the analysis demonstrates that neural network-based forecasts provide reasonably accurate predictions in absolute terms, particularly for cities with higher accident frequencies. Relative errors are more pronounced in smaller cities with low accident counts, highlighting the importance of considering both absolute and percentage error metrics when evaluating model performance. Extending the forecast horizon generally decreases accuracy, although exceptions in medium-sized cities indicate that model performance can vary depending on the interplay between temporal patterns and accident baselines.

5 Discussion

The analysis confirms substantial variation in road accident patterns across the five cities of Wielkopolska, reflecting differences in urban size, traffic density, and infrastructure. Poznań, as the largest city, consistently exhibits the highest monthly accident counts and greatest variability, in line with prior studies linking urban population and traffic volume to accident frequency. Smaller cities such as Piła show low baseline accident numbers, but high relative variability, indicating that sporadic events can disproportionately affect statistical measures. These findings are consistent with literature emphasizing the challenges of modeling rare events in smaller urban contexts.

Neural network models proved effective in capturing nonlinear relationships between meteorological variables, temporal factors, and accident counts. For the 6-month horizon, predictions for larger cities (e.g., Poznań) were relatively accurate in percentage terms, despite high absolute errors. In contrast, smaller cities with low accident counts exhibited high MAPE values, highlighting a well-known limitation in forecasting low-frequency events: small absolute deviations translate into large relative errors. Extending the forecast horizon to 12 months generally reduced accuracy, as expected due to increased uncertainty over time. The exceptions observed in Konin and Kalisz suggest that annual patterns can sometimes enhance the performance of longer-horizon forecasts, especially when short-term variability is unusually high.

From a practical perspective, the results underscore the need for tailored forecasting strategies. In larger urban centers, absolute error metrics (MAE, RMSE) are most informative for traffic management planning, while relative errors (MAPE) are critical in smaller cities where low accident counts may exaggerate perceived forecasting inaccuracy. Policymakers and traffic safety authorities can use these insights to allocate resources more efficiently, prioritize preventive interventions, and set realistic expectations for forecast performance depending on city size and accident baseline.

Several limitations of the study should be noted. First, the dataset covers only 2018–2024; longer historical series could improve model generalization, particularly for low-frequency events. Second, the models rely primarily on meteorological and temporal predictors, without integrating traffic volume, road infrastructure changes, or driver behavior data, which are known to influence accident occurrence. Third, while neural networks are capable of modeling complex

patterns, their "black-box" nature limits interpretability; combining neural networks with explainable modeling approaches could enhance understanding of key accident drivers.

Future research could expand the analysis to additional Polish cities, incorporate real-time traffic and infrastructure data, and explore hybrid modeling approaches combining neural networks with statistical or mechanistic models. Such work would improve both short- and long-term forecasting accuracy and support evidence-based traffic safety management across diverse urban contexts.

A key limitation of the MLP approach is its lack of inherent temporal memory. Future work could explore recurrent architectures (e.g., LSTM or GRU) to better capture long-term dependencies in accident time series. Additionally, incorporating real-time traffic volume, road condition indices, or holiday effects could further improve predictive performance.

6 Conclusions

This study analyzed monthly road accident patterns in five cities of the Wielkopolska region—Piła, Konin, Leszno, Poznań, and Kalisz—over the period 2018–2024 and evaluated the performance of neural network-based forecasts for 6- and 12-month horizons. The analysis revealed that city-specific accident patterns vary significantly: Poznań, as the largest city, exhibits the highest accident frequency and variability, whereas Piła shows the lowest mean accident numbers, with several months recording zero events. Medium-sized cities such as Konin, Leszno, and Kalisz display intermediate values, indicating that urban size and traffic volume strongly influence accident occurrence. Neural network models produced reasonably accurate absolute predictions, particularly for larger cities, while relative forecast errors, measured by MAPE, were high in smaller cities due to the low baseline accident counts, illustrating the challenges of predicting rare events. Extending the forecast horizon from six to twelve months generally reduced accuracy, although minor improvements were observed in Konin and Kalisz, likely reflecting annual accident patterns captured by the models. These findings imply that absolute error metrics are most informative for large urban centers, while relative errors are critical in smaller cities, and that forecasts can guide resource allocation, preventive measures, and planning interventions tailored to city-specific accident profiles. The study is limited by the temporal scope of the dataset, the absence of traffic flow or infrastructure variables, and the inherent “black-box” nature of neural networks. Future research should extend the temporal range, incorporate additional explanatory variables, and consider hybrid or interpretable models to improve prediction quality and understanding of accident dynamics. Overall, this research demonstrates that neural networks can effectively model and forecast monthly road accidents across cities of varying sizes, providing actionable insights for urban traffic safety planning while highlighting the difficulties of predicting low-frequency events in smaller urban areas. City administrations can utilize forecasts for targeted interventions, resource allocation, and proactive traffic management.

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Dynamic digital transportation on local government: a case study on the regional government of the special region of Yogyakarta 2005-2025

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Keywords: digital government, e-government, digital transportation, local government.
Abstract: Bureaucratic reform and digital Transportation have become central to improving public service quality in Indonesia, particularly within the Special Region of Yogyakarta (DIY). Despite significant progress, challenges remain in institutionalizing digital governance as a sustainable agenda. This study formulates the problem of how digital Transportation has unfolded in DIY between 2005 and 2025, and what factors have influenced its dynamics. The objective is to describe and analyze the long-term evolution of digital Transportation in local government, highlighting the interplay of technological, organizational, and policy dimensions. Methodologically, the research adopts a qualitative exploratory approach using a single-case design, relying on in-depth interviews, document analysis, and secondary data to capture the longitudinal process of change. The findings reveal that DIY's Transportation journey progressed from early e-government initiatives under the Jogja Cyber Province Blueprint to the Smart Province framework, supported by regulatory reforms, leadership continuity under asymmetric decentralization, and institutional coordination through Diskominfo DIY. Results indicate that while digital infrastructure, human resource development, and regulatory frameworks have advanced, sustainability remains constrained by hierarchical bureaucratic culture, limited funding mechanisms, and uneven digital literacy. The study contributes theoretically by framing digital Transportation as a co-evolutionary process shaped by socio-technical interactions, empirically by providing a detailed case study of DIY, and practically by offering policy insights for embedding digital governance into long-term institutional frameworks. The discussion emphasizes the need for stronger institutionalization, sustainable funding, and citizen-centered approaches to ensure resilience and inclusivity in future digital governance.

1 Introduction

1.1 Background of study

Bureaucratic reform and digital Transportation of government are central to enhancing public service quality. Digital Transportation is the comprehensive integration of digital technologies—such as cloud computing, IoT, and big data—into government processes to create faster, more transparent, and more participatory services. Digitization involves converting analog data into digital formats, while digitalization and digital Transportation refer to utilizing these technologies to fundamentally change governmental operations and improve public policy and service delivery [1]. Key drivers of digital Transportation in the public sector include political, economic, and technological factors, with an emphasis on adapting to technological innovations to improve government efficiency and reduce bureaucratic barriers.

The evolution of this digital Transportation has led to concepts such as digital government, e-government, and smart government, which collectively encompass advanced uses of information and communication technologies in governance. Smart government represents a sophisticated stage of modernization, where disruptive technologies enhance interactions between citizens and government, decision-making, and overall quality of life [2]. Essential components for developing smart government include robust digital infrastructure, AI, big data, and blockchain technologies to improve service efficiencies and decision-making quality.

Regulatory frameworks, governance policy formulation, effective human resource management, and data security risk management are critical to successful implementation. Public participation enhances transparency and accountability, and privacy measures protect citizens' personal data, fostering trust in digital services. Smart government architecture

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comprises five essential layers: the User Layer for citizen interaction; the Application Layer for service delivery; the Control Layer for regulatory compliance; the Database Layer for data management; and the Infrastructure Layer for foundational technology support [3].

Challenges to e-government implementation in developing countries include a lack of strategic planning, obsolete technology, rigid bureaucracy, insufficient skills, and the digital divide, all of which require focused policy support, planning, and infrastructure improvements. In Indonesia, the push for a "Digital Government" under the Electronic-Based Government System (SPBE) policy highlights ongoing initiatives to enhance public service effectiveness and transparency. The Special Region of Yogyakarta exemplifies progress in digital Transportation, consistently achieving high rankings under SPBE evaluations. As shown in Figure 1.

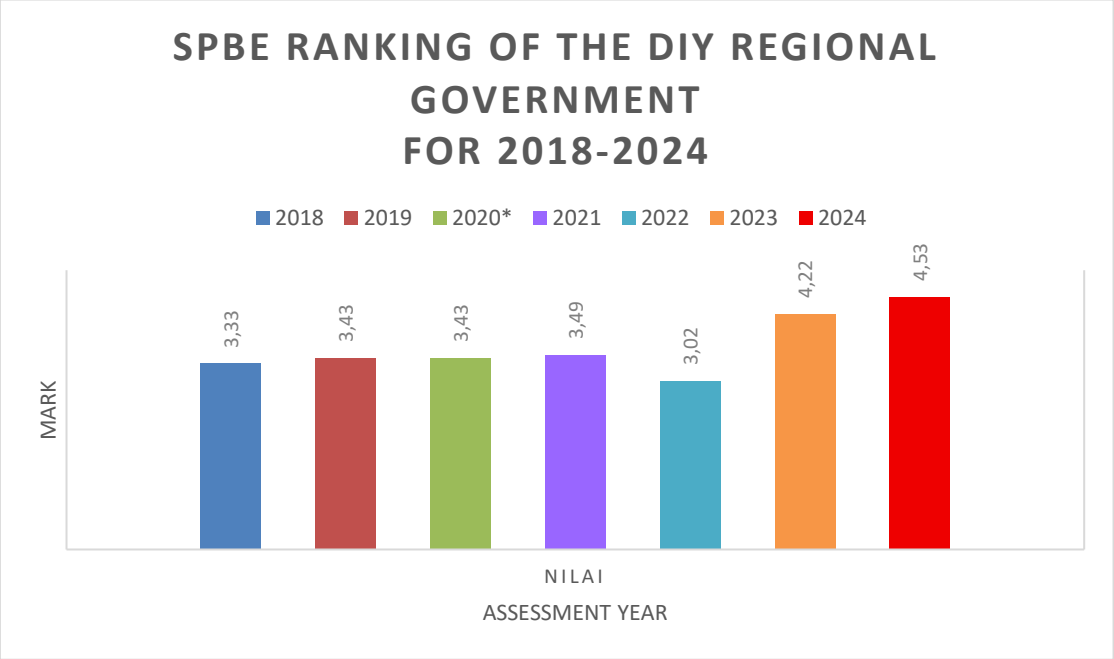


Figure 1 Ranking of the DIY regional government
Source: Ministry of Administrative and Bureaucratic Reform, 2025

The province of DIY (Yogyakarta Special Region) in Indonesia was the first to implement the e-Government concept through the Jogja Cyber Province Blueprint, established under Governor Regulation No. 42/2006. This regulation positions DIY as a "model province" focused on customer-oriented public service Transportation using information and communication technology (ICT) to enhance its competitive power. Support institutions such as the Innovation Group, Change Management, and JCT Training Center strengthen human resource capabilities and organizational culture across sectors, including policy-making, IT, human resources, and finance [4].

The vision of e-Government has evolved into the Smart Province concept, outlined in the Jogja Smart Province Regional Action Plan (Governor Regulation No. 46/2019). This plan identifies a creative and innovative approach by local government and stakeholders to address strategic issues through technological optimization, data integration, and regional collaboration. The concept broadens the focus beyond public service to encompass Smart Society (high digital literacy), Smart Living, Smart Culture, Smart Environment, and Smart Governance, shifting from mere digital services to a comprehensive smart ecosystem [5].

Governor Regulation No. 131/2021 further delineates the Grand Design of the region from 2022 to 2042, reinforcing long-term cultural preservation and innovation while emphasizing a digital ecosystem as a pillar of excellence. The 2024 Governor Regulation No. 32/2024 integrates and updates prior initiatives, revoking earlier regulations to reflect current developments. This comprehensive plan maintains stakeholder collaboration and technological innovation, incorporating additional dimensions like Smart Branding and Smart Economy.

Institutionally, the Communication and Information Service (Diskominfo DIY) serves as the main coordinator for smart province digital policies, overseeing the implementation of the 2024 plan. The previous regulations established inter-departmental teams for human resources development and emphasized community digital literacy, which continues to evolve in the current planning. Funding for these initiatives remains dependent on the DIY regional budget (APBD) and other legitimate sources, with no long-term commitment ensuring sustainability without routine budgeting [6].

Governor Regulation No. 46/2019 includes performance indicators and a roadmap for assessing sectors involved in the Smart Province initiative. The 2024 plan represents a systematic integration of these indicators into the regional

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planning documents (RPJMD) and national standards (SNI), establishing a framework for ongoing evaluation of the Smart Province initiative. Despite significant strides, digital Transportation in DIY has not yet been fully institutionalized into a cohesive, sustainable governmental agenda. It currently relies heavily on sectoral coordination led by Diskominfo and key actors without robust cross-regional authority. The unique political context, characterized by asymmetrical decentralization and historical privileges, imposes both challenges and opportunities for governance [7].

From a theoretical perspective, the unique asymmetric decentralization allows the region to maintain a stable political leadership structure, embodied by the Sultanate, which facilitates consistent long-term policy direction. However, challenges related to resource allocation and integration of IT infrastructure persist. Transportational leadership is highlighted in the context of public bureaucracy as a catalyst for enhancing effectiveness and commitment while fostering a collaborative culture that supports innovation. Yet, hierarchical cultures and resistance to change can obstruct progress, presenting ongoing challenges to digital competency within the public sector [8].

1.2 Research question and research objectives

The questionnaire study was arranged based on the opportunity selected for the above research. Question studies help researchers design directed and methodological research. Research objectives give direction and focus to research.

Question of study:

- How does digital Transportation in the government area study the case of the Yogyakarta Special Region Government 2005-2025?
- What factors influence the dynamics of digital Transportation in the government area studies case of the Yogyakarta Special Region Government, 2005-2025?

Research purposes

This study aims to describe the dynamics of digital Transportation in local government, a case study of the Yogyakarta Special Region Government in 2005-2025.

1.3 Benefits of research

This is for enriching or modifying theory, practice, and digitalization from e-government to the digital government sector at the government level, local (provincial), and special levels, namely the Special Region of Yogyakarta Province. Implications of the research. This research can contribute to a theoretical basis for the modification theory of digital governance at the provincial government level.

1.4 Research authenticity

This research contributes to the development of studies on the digital Transportation of local government by viewing it as a longitudinal organizational change process influenced by interactions among technological, organizational, and policy environment factors. Theoretically, this study views digital Transportation in government as a long-term evolutionary process. Methodologically, it uses a longitudinal approach to examine the implementation of digital policies over 2005–2025, thereby explaining the influence of regulatory changes, organizational restructuring, and leadership dynamics on the sustainability of digital Transportation at the regional level. Empirically, this study examines digital Transportation within the context of asymmetric decentralization in the Special Region of Yogyakarta (DIY), characterized by stable political leadership and specific institutional authority. Thus, this study contributes to explaining how regional institutional configurations influence the rhythm and direction of digital Transportation in government at the subnational level.

2 Literature review

2.1 Digital transportation in the business sector

Digital Transportation has become a significant concept in strategic management and information systems over the past two decades, particularly in response to technological disruptions and increased competition in the digital economy. It is viewed not merely as a technology adoption process but as a comprehensive organizational change that affects business models, structures, and value creation mechanisms. According to [9], digital Transportation is defined as an ongoing process that induces significant changes within an organization by integrating various interconnected digital technologies. The literature has highlighted a lack of consensus regarding the definition of digital Transportation, with some using the analytical distinction between digitization, digitalization, and digital Transportation as proposed by [10]. Digitization involves converting analog information to a digital form, while digitalization uses digital technologies to enhance existing processes. In contrast, digital Transportation embodies a significant strategic shift encompassing changes to organizational structure, business models, and customer interactions.

Recent studies emphasize that digital Transportation involves a multidimensional approach encompassing digital technology integration, organizational strategy, work culture, and leadership, thereby facilitating comprehensive changes across the organization. It acts as a mechanism for strategic renewal, allowing organizations to adapt to more data-driven service ecosystems [11]. This transition often utilizes advanced technologies, including blockchain, the Internet of Things (IoT), and artificial intelligence, to foster sustainable practices and improve resource efficiency. Organizational success in digital Transportation is largely contingent upon internal factors, such as digital culture, leadership, and employee engagement. Transportational and adaptive leadership is pivotal in mitigating resistance to change and promoting innovative practices [12]. Furthermore, the development of organizational learning and knowledge management capabilities is crucial for achieving higher digital maturity and navigating the complexities of the digital environment.

2.2 Digital transportation in the public sector

2.2.1 Digital transportation as the shift from digitalization to transportational institutional

The literature on digitalization in the public sector has evolved from e-government discourse, which emphasizes the use of information and communication technology (ICT) for service delivery. Initially, technology was viewed primarily as a tool for administration, aimed at enhancing operational efficiency and service quality [13]. However, digital Transportation within public organizations extends beyond mere administrative procedures; it encapsulates a fundamental change through the integration of digital technology in governance decision-making processes [14]. This Transportation reflects a shift from using technology solely as an administrative tool to addressing socio-technical factors that influence organizational structure and data-driven decision-making practices.

2.2.2 Shift paradigm: from technology-centric to socio-technical governance

Digital Transportation in government is increasingly understood as a socio-technical phenomenon involving interactions among digital infrastructure, organizational capacity, leadership, bureaucracy, and external regulatory pressure [15]. Perspective: This mark shift is important in the technology-centric approach, recognizing that the implementation of digital technology in the public sector is ongoing in complex organizations and is governed by relatively rigid institutional norms and stable. A number of studies show that the adoption of digital technologies such as artificial intelligence (AI), big data analytics, cloud computing, Internet of Things (IoT), and blockchain does not automatically produce improved performance for government if not accompanied by changes in organizational culture and governance mechanisms policy [16]. In this context, digital Transportation is not only about modernizing infrastructure technology, but also about organizations' ability to publicize and integrate data into practice to inform policy decisions.

2.2.3 Theoretical debate: technological determinism versus institutional capabilities

In practice, the implementation of digital Transportation in government organizations is often influenced by regulatory dynamics, leadership rotation, bureaucratic structural reconfiguration, and cross-sectoral system integration that occurs gradually and not always linearly [17]. This indicates that digital government Transportation cannot be adequately understood through an analytical framework that statically separates technological factors from organizational capacity. Digital Transportation in the public sector is better understood as a process of institutional adaptation that evolves through the configuration of interactions among digital technology, organizational capacity, and external policy pressures. static and oriented towards factors influencing innovation adoption at a single point in time [18]. Not yet, in a way that is explicit, capable of explaining the dynamics of change in ongoing organizations longitudinally in the digital government Transportation process.

2.3 Electronic government (e-government)

The beginning of e-government development is marked by the prevalence of the New Public Management (NPM) paradigm, managerial reform, and a positive view of technology in public administration. During this period, e-government is understood as the implementation of information and communication technology (ICT) to increase efficiency, effectiveness, transparency, procedural fairness, and the quality of public service. Research has begun to emphasize the digitalization of administrative processes, the development of government websites, the management of information systems, and service-based automation such as licensing, taxation, and population administration [19].

The literature presents classic e-government technology as an instrument of rational repair for the lack of bureaucratic tradition, which is characterized as slow, hierarchical, and unresponsive. Framework-neutral work to nature and universal basis technology, allowing its implementation across various government contexts. Research: This study identifies striking similarities across various e-government maturity models that put forward linear and gradual development, starting with web presence, followed by interaction, transaction, integration, and culminating in Transportation [20]. These models are widely adopted in research and policy because they provide a straightforward and measurable framework.

Research in this field highlights technical elements such as bandwidth, security system, and the usefulness of the website as important factors for success. The institutional and governance-oriented camp denies this assumption, arguing that structure, organization, leadership, regulation, and culture and bureaucracy are far more influential than technology itself. Methodological criticisms also emerged as a theme central to the beginning of e-government literature. Many studies use a quantitative descriptive approach, including surveys of e-government readiness, government website indexes, and cross-country or regional benchmarking [21]. These methods, although beneficial for mapping early, have faced criticism because their analysis is inadequate for the process, stakeholders' interests, and the dynamics involved in policy implementation. Early e-government literature is more proficient at discussing the extent of technology adoption, but not deep enough in explaining the reasons and mechanisms behind the success or failure of digital policy.

2.4 Group instrumental and managerial approaches

They, in a way, generally agreed that e-government is the use of ICT to increase efficiency, effectiveness, transparency, and quality of public service. This is reinforced by the [22], which explicitly states that e-government can transform the relationships between government and citizens and between government and the business world through digital technology. Pro-e-government literature starts from the assumption that technology is neutral and progressive, so that ICT adoption is believed to produce more government Good in an automatic way.

2.5 Group approach institutional and political

On the other hand, the group's second question claims normative e-government as a universal solution. [23] is one of the academics who began to criticize the instrumental approach, stating that e-government is often perceived as a technology project, not a governance reform. He confirms that technology is only effective when accompanied by changes in organizational structure and cultural bureaucracy. Further criticism was offered by [24], who argued that e-government has the potential to strengthen state control rather than expand democratic participation. According to him, e-government can increase internal efficiency, but not in a way that automatically produces openness or accountability to the public.

2.6 Evolutionary critique: from e-government to digital government

Criticism of the definition of classic e-government has led to the emergence of an evolutionary approach. [25] argue that e-government is too narrow because it focuses on digital services rather than on engineering repeatable government functions. They introduce the concept of Digital-Era Governance as a response to the failure of early e-government approaches. This was expanded by [26], who systematically criticized the next generation of e-government as digitization-centric. According to Janowski, e-government is at the stage of beginning to understand the dynamics of the political and social spheres, so it needs to transform into a contextual digital government and digital governance. It criticized the domination indicator efficiency in the definition of e-government. They emphasize that the success of e-government should be measured by public value, including trust in public institutions, participation, and access to justice.

2.7 Influencing factors: the success of e-government

Success factors in partial implementation of e-government include the availability of ICT infrastructure, the capacity of human resources, and support budget [27]. The literature shows that related factors alone are insufficient. Research conducted by shows that leadership, political and administrative clarity, regulation, governance information, and coordination across organizations are the main determinants of e-government success. From a coevolutionary perspective, success occurs when innovative technology coincides with adaptive organization and simultaneous changes in institutions.

2.8 E-government in DKI Jakarta

In the Indonesian context, DKI Jakarta is often positioned as a leading regional digital government through the development of Jakarta Smart City, data integration across OPDs, and the use of digital dashboards to handle crises, especially during the Covid-19 pandemic. Studies show that digital innovation in DKI Jakarta increases the responsiveness of public services and the coordination of policy data-based [28-31]. However, the study clearly confirms that DKI Jakarta's success cannot be separated from its status as an area with special fiscal capacity and strong political leadership. Data integration across OPDs still faces resistance from organizational and sectoral egos and dependence on tall-figure leaders . The literature also highlights the sustainability of risk post-transition digital policy leadership, as it is not yet fully institutionalized in regulations and bureaucratic routines.

3 Research method

3.1 Research approach

This qualitative exploratory study adopts a holistic, single-case design to examine phenomena related to policy and governance in digital government. The approach seeks to provide an in-depth understanding of these dynamics through

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comprehensive analysis rather than merely descriptive observation. The research begins with empirical facts gathered directly from the field, where researchers actively engage in the context, observing phenomena, systematically recording data, interpreting findings, and reporting conclusions. Consequently, the study's findings offer potential contributions to theoretical propositions and can inform concepts and principles based on empirical realities. Data was collected through in-depth interviews, document analysis, and meticulous research documentation. The analysis involved enriching information, exploring relationships, comparing data sources, and identifying emerging patterns. The results are presented as an analytical narrative that elucidates the conditions and dynamics of the studied phenomenon while addressing the "how" and "why" of digital policy and governance issues.

3.2 Case selection

This study examines the digital Transportation journey of the government in the Special Region of Yogyakarta (DIY) over the last 25 years. It traces the evolution from initial information technology implementation in public administration to the development of e-government and the shift towards digital governance. The choice of DIY as a case study is due to its unique governance structure, which includes distinctive decision-making processes and institutional arrangements influenced by asymmetric decentralization as per Law No. 13 of 2012. The Transportation in DIY is characterized by an evolutionary rather than instantaneous process, supported by information technology since the late 1990s. It has progressed through the establishment of an e-government system that integrates services across organizations and utilizes data for decision-making, particularly highlighted during the post-COVID-19 period.

This research takes a holistic approach to digital Transportation, addressing various dimensions such as technology, policy, leadership, organizational capacity, institutional configuration, data governance, and interactions between governmental and non-governmental actors. It aligns with co-evolutionary frameworks, indicating that digital governance arises from dynamic interactions among diverse elements within specific social and political contexts. The research not only describes the developmental stages of government digitalization but also seeks to understand the motivations behind this Transportation in a privileged region. The findings aim to contribute theoretically to the study of digital government by elucidating the dynamics of digital Transportation in asymmetrically decentralized regions and enhancing the discourse on digital governance in Indonesia, making it more contextual.

3.3 Unit of analysis

This is the digital Transportation process of government in the Special Region of Yogyakarta (DIY), which includes the evolutionary application of technology and information, e-government development, and the embodiment of digital government in the context of privileged areas. The unit of analysis is understood as a holistic unity, analyzed longitudinally through the dynamic interaction among policy, leadership, institutions, organizational capacity, data governance, and the use of digital technology within the government organization. Thus, research. No separate units of analysis within organizational sub-units are certain; rather, the focus is on the dynamics of digital Transportation of the DIY government as a case study.

3.4 Grid study

In case study research, a research framework is required as an analytical tool to ensure the research process is systematic, directed, and remains focused on the research objectives. This framework serves as a guide for directing data collection and analysis to ensure it remains within the defined case boundaries. Furthermore, this observation framework will be tested and deepened through in-depth interviews. Details of this research's observation framework are presented in Table 1.

Table 1 Research grid

Grid Study	Information	Method of collecting data
Co- evolution identification e-government Transportation towards digital government	In the initial phase, the use of technology information in the government sector focused on improving service efficiency and accessing information, with changes in organizations and institutions still limited and influenced by a relatively stable bureaucratic culture. The transition phase, interaction technology, and organization are more intensive through integration services and coordination across device areas, while the institutionalization of digital Transportation is heavily influenced by leadership and culture. In the advanced phase, interaction technology, organizations, and institutions are more integrated and consolidated, so that	Interview Secondary Data

	digital Transportation is oriented towards the creation of a public mark, community participation, and the sustainability of governance. HR, Budget, related regulations, working methods between units Influential factors	
Identify influencing factors	Regulation Policy applicable national Leadership factors Regional development planning Division of government affairs Collaboration and partnership	Interview Secondary Data

Source: Analysis author, 2026

3.5 Data collection method

In the study of digital Transportation within the government of Yogyakarta Special Region, both primary and secondary data are utilized to provide a comprehensive understanding. Primary data, which serves as the main source, is gathered through direct interactions between researchers and the subjects involved in the Transportation process. This qualitative information encompasses the experiences, perceptions, knowledge, and practices of key actors in digital Transportation. Notable primary data includes in-depth interviews, coordination patterns, and dynamic behaviors encountered during the study. Conversely, secondary data, which supports the primary findings, is derived from various written and documented sources. This includes policy documents, legislative regulations, strategic plans, performance reports, institutional archives, and official publications pertinent to the government's digitalization efforts. Moreover, secondary data comprises academic literature, research reports, and relevant scientific publications, which enhance the analysis and provide a theoretical context to the empirical findings.

3.6 Primary data collection

In this research on the digital Transportation of the Yogyakarta Special Region government, primary data was primarily collected through in-depth interviews and documentation. The in-depth interviews involved key informants directly engaged in policy formulation, planning, and execution of digital Transportation initiatives. These semi-structured interviews allowed for a comprehensive exploration of various factors influencing digitalization, including leadership roles, institutional dynamics, and cultural governance aspects. Key informants included members of the DIY Communication and Information Service, the Regional Development Planning Agency, and other relevant stakeholders. The informants were selected using snowball sampling, focusing on in-depth knowledge and relevance to the research topic, allowing for continuous referral until information saturation was achieved.

Documentation supported the research by collecting both primary and secondary data. Primary documentation involved recording interviews with informants, capturing photos of research activities, and noting the infrastructure and digital systems relevant to the government's digital initiatives. This provided empirical evidence of the observed digital Transportation practices. On the other hand, secondary documentation included gathering information from various written sources such as government policies, regulations, and official reports, which helped to contextualize and strengthen the analysis of the primary data. The combination of these methods ensured a robust approach to understanding the dynamics of digital Transportation in the Yogyakarta Special Region government.

3.7 Secondary data collection

The study utilizes secondary data, which includes official documents, performance reports, and policy archives from the Yogyakarta Special Region Government (DIY) to provide context and support the analysis of primary data related to the digital Transportation of government. The collected secondary data encompasses several types:

Development planning documents like the Long Term Regional Development Plan (RPJPD) and Medium Term Regional Development Plan (RPJMD) guide area policy development and the role of information technology, e-government, and digital governance in sustainable planning. Information Accountability Reports (LKPJ) from the Governor covering 2006-2026, identifying policy dynamics, priority programs, and achievements concerning technology information utilization and public service digitalization across government periods. Government Performance Accountability Reports (LAKIP) from strategic agencies involved in digital governance, aiding the analysis of performance indicators, programs, and related activities within the information governance system, and integration of digital services.

Technical planning documents related to the digital government sector, including the Yogyakarta Special Region e-Government Masterplan and infrastructure development plans prepared by local authorities. Supporting policy documents

for government digitalization, focusing on regional data center management, public service application integration, interoperability standards, and data governance regulations. Legal regulations and local government products, detailing regional laws, governor regulations, and statutes for regional organization and governance implementation of e-government and digitalization. Operational activity data, like program implementation reports from the DIY Communication and Information Service, system implementation documentation, and cross-agency coordination reports. The use of these secondary data sources provides a comprehensive understanding of the ongoing digitalization efforts in the Yogyakarta Special Region, facilitating triangulation with primary data gathered through interviews to enhance the study's validity. As shown in Figure 2.

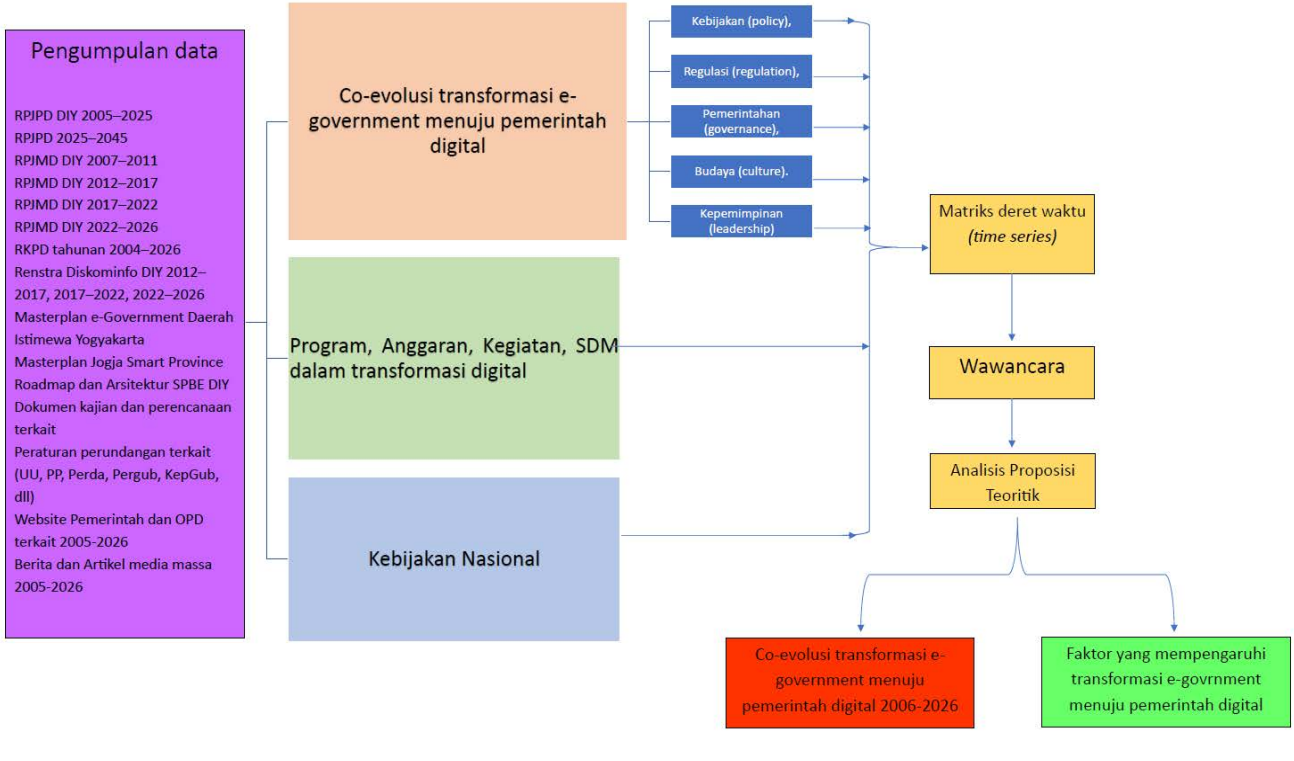


Figure 2 Analysis flow

3.8 Data analysis

Data analysis in case studies is crucial for quality inference and theoretical contributions. Yin [29] identifies it as a systematic process linking empirical evidence with research propositions. In longitudinal studies, it tracks temporal changes, recurring patterns, and explanatory mechanisms, emphasizing digital Transportation processes over time. The study focuses on the Yogyakarta Special Region Government, analyzing its digital evolution through four strategies: pattern matching, explanation building, logic models, and time-series analysis. The analysis follows structured stages: organizing secondary data, exploring technological and organizational interactions, constructing time-series matrices, identifying influencing factors, and preparing narratives. This approach highlights the dynamics of digital Transportation and informs policy recommendations, shaping understanding of government digitalization at the subnational level.

3.9 Framework of study

In conducting research, a systematic flow is required so that the research process is directed, focused, and structured. This flow poured in framework research presented in Figure 3.

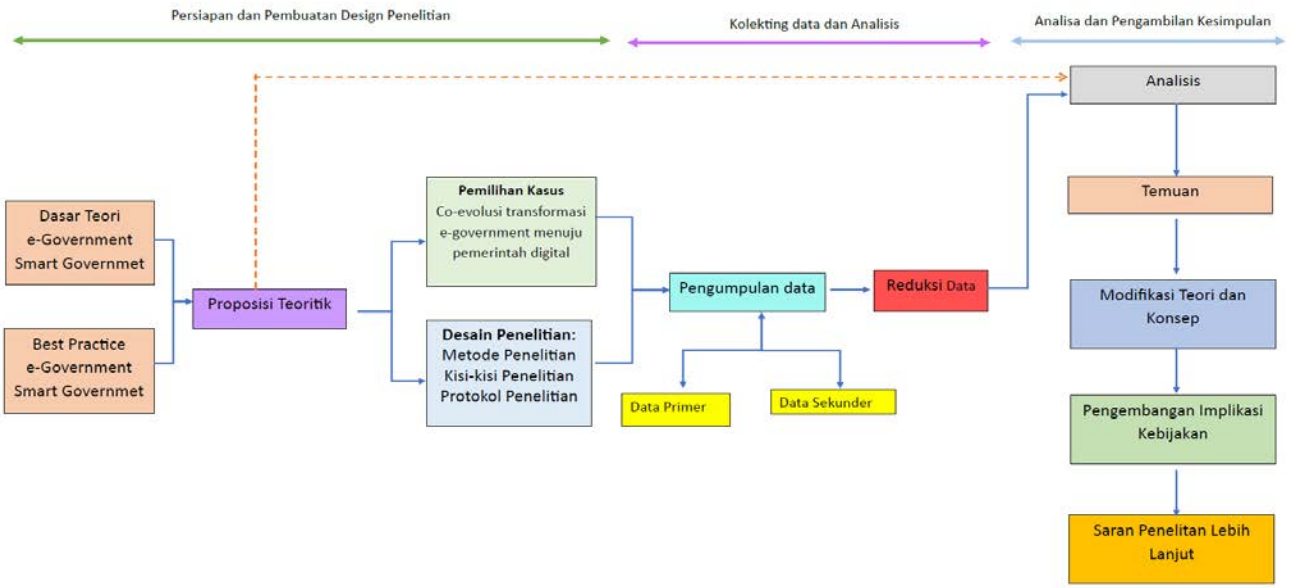


Figure 3 Research framework
Source: Visualization Writer based on Yin [29]

4 Results and discussions

4.1 Analysis each period in the digital transportation of the regional government of the special region of Yogyakarta 2005-2025

The Special Region of Yogyakarta initially implemented ICT use to improve bureaucratic performance. From this, it then undertook a digital Transportation to realize effective, efficient, transparent, and accountable governance in providing excellent and quality public services to the community. The Regional Government of the Special Region of Yogyakarta (Pemda DIY) implemented the digital Transportation in stages, adapting to ongoing dynamics both at the regional level and to national policies. The two-decade journey to realizing digital Transportation in good governance has seen changes categorized into three periods. Outline periodization of digital Transportation in the DIY Regional Government can be seen in Figure 4 below:



Figure 4 Period digital transportation in local government, special region of Yogyakarta 2005-2025
Source: author's analysis results, 2026

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4.1.1 Period 1: foundation laying (readiness) 2005-2015

National policy context and the early development of information and communication technology (ICT) in DIY

The development of smart government in Indonesia began with early e-government efforts in the 1990s, transitioning from typewriters to computer-based systems. In 1992, policies were introduced to establish Electronic Data Processing Offices at the regional levels, influencing local regulations, particularly in Yogyakarta. A significant advancement occurred in 2000 with the formation of the Indonesian Telematics Coordination Team, which aimed to enhance telematics technology and bridge the digital divide. The launch of the Government Online (G-Online) initiative in 2001 marked a strategic move towards integrating technology into governance, promoting transparency and efficiency. In 2003, a national policy consolidated these efforts, emphasizing user-centered electronic public services and requiring coordinated strategic framework development across levels of government. Regional regulations in the following years, especially in Yogyakarta, realigned governmental functions, leading to the establishment of integrated telecommunication departments, reflecting a shift towards effective digital governance. However, this evolution faced challenges in data integration and consistent policy alignment, underscoring the need for strong digital leadership for future advancements towards a comprehensive smart government.

Technology

The national policy on the implementation of Information and Communication Technology (ICT) in government organizations, formalized by Presidential Instruction Number 3 of 2003, emphasizes ICT as a strategic tool for enhancing management systems and government processes. This initiative aims to create a more effective, efficient, transparent, and accountable e-government structure. The Special Region of Yogyakarta (DIY) has embraced this policy through Regulation Governor Number 42 of 2006, establishing the Blueprint for Jogja Cyber Province, focusing on Digital Government Services (DGS) to improve public service quality by integrating ICT. Since 2002, DIY has developed technological infrastructure, including LAN and WAN networks, facilitating inter-unit communication within government organizations. The Jogja Cyber Province Blueprint includes nine flagship DGS programs tailored to various sectors, such as agriculture, health, education, and tourism, demonstrating a sectoral approach to digital services.

Additionally, support programs have been created to enhance internal government services and public utilities, expanding the e-government ecosystem. From 2015 to 2016, the DGS expanded to cover multiple fields, underscoring the commitment to utilize ICT strategically in governance. This digitalization extends beyond traditional sectors, influencing welfare, environmental, and cultural issues. Consequently, the DGS concept promotes Transportation towards a citizen-centric governance model, enhancing public access to information and services, fostering greater participation in governance, and ultimately improving the welfare and competitiveness of the Yogyakarta population.

Organization

The digital Transportation of the Yogyakarta Province (DIY) from 2005 to 2015 reflects ongoing bureaucratic reform post-1998, which predominantly focused on transparency, accountability, and administrative efficiency without significant structural changes. The introduction of Information and Communication Technology (ICT) was aimed at modernization rather than a complete Transportation of governance. The Jogja Cyber Province (JCP) initiative showcased compliance-based digitalization rather than a strategic overhaul, leading to siloed sectoral systems rather than integrated services. The 2006 earthquake prompted the launch of Digital Government Services (DGS) as a crisis response, aimed at improving data collection and coordination, but it failed to resolve systemic bureaucratic fragmentation. While DGS expanded across various public sectors, it reinforced existing organizational silos and did not foster integrated data management. Limitations in leadership, human resources, infrastructure, and organizational culture hindered the effectiveness of DGS during this period, indicating a gap between policy design and practical implementation. The Transportation was more reactive than proactive, revealing a critical need for improved digital governance and integration for future progress.

Institution

The period from 2005 to 2015 marked the initial phase of establishing digital government institutions in Yogyakarta Province, Indonesia, amidst post-1998 bureaucratic reforms. During this time, digitalization was not seen as a comprehensive governance Transportation but as a modernization effort aimed at enhancing efficiency, transparency, and procedural order. The agenda for enhancing information and communication technology (ICT) within the provincial government gained legitimacy through national policies, particularly the Presidential Instruction No. 3 of 2003, which encouraged electronic government systems. Empirical findings indicate that the provincial government of DIY successfully built a foundational digital institution through internal regulations, core application systems, and ICT infrastructure, exemplified by over 2,700 connected computers and significant bandwidth. However, considerable limitations were identified. The digitalization process remained fragmented and sectoral, with each regional government agency (OPD) developing its own standards, leading to poor data integration. Additionally, a notable shortage of

technically skilled human resources constrained the effective management and development of digital systems. Moreover, the culture of data management and public information transparency did not consistently develop, indicating that despite the presence of digital systems, practices were not standardized. This period established a formal framework and technical capacity for further digitalization, yet it highlighted issues such as system fragmentation, inadequate data integration, and insufficient internalization of digital governance values. These challenges signal the need for regulatory adjustments, organizational restructuring, and stronger digital leadership for future Transportation.

Factors that Influence in This Period

Government digital Transportation in the Special Region of Yogyakarta Province (DIY) from 2005 to 2015 was influenced by various structural, institutional, and contextual factors, leading to partial and sectoral achievements. Key influencing factors include:

- Policy Factors: The national e-government policy emphasizes compliance over substantive governance, leading to a lack of internalization of the Digital Government Services (DGS) blueprint among local agencies, which operate separately rather than cohesively.
- Organizational Factors: Bureaucratic structure remains hierarchical and fragmented, preventing effective cross-organizational coordination and integration, resulting in disconnected information systems across sectors.
- Crisis Factors: The 2006 earthquake highlighted the limitations of conventional bureaucracy in managing disaster response, necessitating an integrated information system, but lessons learned were not institutionalized post-crisis.
- Technology Factors: While significant advancements in ICT infrastructure were made, the focus on sectoral applications led to poor data integration capabilities across agencies.
- Human Resource Factors: Dependence on individual technical capacities limits the sustainability of DGS, as not all agencies possess the necessary skilled personnel for independent technical management.
- Cultural Factors: Organizational culture does not treat data and information as strategic assets but rather as administrative burdens, hindering documentation and transparency practices.
- Infrastructure and Planning Factors: Incremental and uncoordinated infrastructure development restricts DGS effectiveness, resulting in unequal digital service availability across agencies.
- Regulatory and Organizational Change Factors: Changes in regulations governing organizational structures disrupt DGS governance and continuity, diminishing its role as a cross-sector governance tool and slowing down data integration efforts.

Overall, these factors demonstrate a complex interplay that has hindered a cohesive digital Transportation in the region.

4.1.2 Period 2: initial data integration period and strengthening cross-local government collaboration (prov-district/city) 2016-2018

National policy context and information technology (ICT) development

The Transportation of digital government and smart cities in Indonesia is grounded in a multi-layered national policy framework, specifically articulated in Law Number 23 of 2014 and Government Regulation No. 18 of 2016, which empower regional governments to innovate in governance and public services. The central government's 2017 initiative, Movement Towards 100 Smart Cities, signals a shift to an integrated approach for urban development. This includes the establishment of Presidential Regulation No. 95 of 2018 on the Electronic-Based Government System (SPBE), which aims to standardize digital governance. In the Special Region of Yogyakarta (DIY), which has unique constitutional privileges, the digitalization agenda is integrated into regional development planning (RPJMD 2017–2022), emphasizing human-centered development through improved public services. The leadership in DIY plays a crucial role in adapting national policies to its specific context, informed by a philosophy that encourages moral legitimacy and strategic governance changes.

Technology

The period from 2016 to 2018 in the Special Region of Yogyakarta marks a phase of technological consolidation in the realm of digital government. This stage is characterized by foundational efforts to integrate data and enhance connectivity among Regional Apparatus Organizations (OPD), alongside fostering collaborative opportunities between provincial and district/city governments. The information and communication technology (ICT) infrastructure, particularly the Fiber Optic network and increased internet bandwidth, signified substantial progress. Nevertheless, while the technical connectivity improved, substantive integration and standardization of data remained inadequate. The Blueprint Jogja Cyber Province, aimed at developing e-government, served as the normative framework, prompting sectoral applications in various strategic OPDs. However, evaluations indicated that the blueprint had not been fully

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operationalized, leading to fragmented practices and application silos. This situation hampered broader cross-sector and cross-regional collaborations.

Efforts toward data integration became clearer with the establishment of the Integrated Development Management Center (IDMC) and a regional data warehouse. While the IDMC aimed to provide real-time operational oversight, it was mostly limited to provincial control without effective collaboration with district/city governments. The Jogja Smart Province (JSP) initiative sought to extend beyond basic e-government services towards smart governance. Yet, it faced challenges regarding robust data governance, such as a lack of agreements and clearly defined responsibilities. Public service applications like Jogja Istimewa and e-Lapor DIY enhanced transparency and interaction quality between the government and citizens. However, these remained largely informational rather than integral to cross-regional decision-making.

Throughout these years, the Yogyakarta Regional Government focused on building the ICT foundation necessary for future data integration. In 2016, a significant push was noticed in the establishment of a digital government infrastructure, focusing on internal efficiency. The subsequent year saw a conceptual shift with the introduction of data-driven decision-making tools like the IDMC, yet collaboration was still predominantly vertical and province-centric. By 2018, the IDMC had evolved into a public portal, facilitating broader data integration and supporting public services. Although advancements were made in promoting transparency and openness, the actual effectiveness of collaborative decision-making systems remained limited, emphasizing the necessity for better human resource readiness and enhanced data analytics capabilities among OPDs and local governments.

Organization

In the Yogyakarta Special Region Government, the integration of poverty data has evolved from a technical endeavor to a politically mediated collective agenda, essential for addressing sensitive inter-organizational needs. Initially, distinct definitions of poverty data across various regional government agencies (OPD) created challenges in consistency and alignment, leading to resistance rooted in autonomy concerns. This resistance reflects underlying power dynamics within decentralized bureaucratic organizations rather than mere technical failures. The symbolic leadership of Sri Sultan Hamengku Buwono X played a crucial role in overcoming these tensions by framing data integration as a moral duty aligned with the common good, rather than an administrative obligation.

The process revealed that success hinged on navigating the negotiations among various stakeholders, including the recognition of poverty data as not just a statistic, but a source of power and legitimacy in policymaking. Informal communication and collaborative discussions facilitated by technocratic actors proved essential in fostering cooperation. As trust and shared understanding developed through initial successes, perceptions of data integration shifted; it began to be seen as a necessary strategy for enhancing policy targeting and minimizing inter-agency conflict. This evolution into a more unified approach toward poverty data illustrates the complexity of governance in fragmented systems and highlights the importance of legitimate authority and trust in collaborative efforts.

4.2 Key insights

The figure 5 presents a three-field Sankey diagram linking cited references (CR), authors (AU), and merged keywords (KW_Merged), revealing the intellectual and thematic structure of the research domain. A dominant insight is the central influence of key scholars, particularly Minari TP, Pisani LP, Inverardi P., and De Sanctis M., who act as major intellectual bridges between foundational references and thematic outputs. The thickness of flows indicates that these authors significantly consolidate prior knowledge into current research streams. Notably, Inverardi and De Sanctis appear both as cited references and active authors, suggesting high continuity and self-reinforcing scholarship within the field. From a thematic perspective, the most prominent keyword is “laws and legislation,” indicating that the field is strongly anchored in regulatory and legal analysis. This is complemented by secondary but interconnected themes such as “human,” “public health,” “law,” and “climate change,” pointing to an interdisciplinary convergence between legal frameworks and societal challenges. Emerging topics like “decision making,” “sustainability,” and “risk assessment” suggest a shift toward applied and policy-relevant research. Additionally, smaller nodes (e.g., Abdulai SF, Guo Y) connect to niche keywords, reflecting fragmented but growing sub-discourses. Overall, the diagram highlights a core-periphery structure, where a few influential authors and legal-centric themes dominate, while sustainability and health-related issues are expanding the field’s scope.

Figure 6 illustrates a life-cycle analysis of annual publications using a logistic growth model, providing insight into the maturity and future trajectory of the research field. The reported $R^2 = -\infty$ indicates a poor or invalid model fit, suggesting that the logistic function does not appropriately capture the empirical publication trend. This may result from insufficient or highly irregular observed data, making the predictive validity of the model questionable. The model identifies 2026 as the peak year, with approximately 200 publications, marked by the red dashed vertical line. However, the subsequent forecast (blue dashed line) shows an abrupt and unrealistic decline to near-zero publications shortly after 2027. In a typical scientific domain, publication output rarely collapses this sharply, indicating model misspecification or overfitting. The observed data points (blue dots) appear sparse and limited in temporal coverage, which likely undermines

the robustness of the logistic estimation. Additionally, the absence of a gradual saturation phase—expected in standard innovation diffusion or bibliometric life cycles—further weakens the interpretation. Substantively, this figure suggests that the field may either be prematurely modeled as mature or lacks sufficient longitudinal data for reliable forecasting. A more appropriate approach would involve alternative models (e.g., exponential smoothing, ARIMA, or piecewise regression) and extended datasets to better capture growth dynamics.

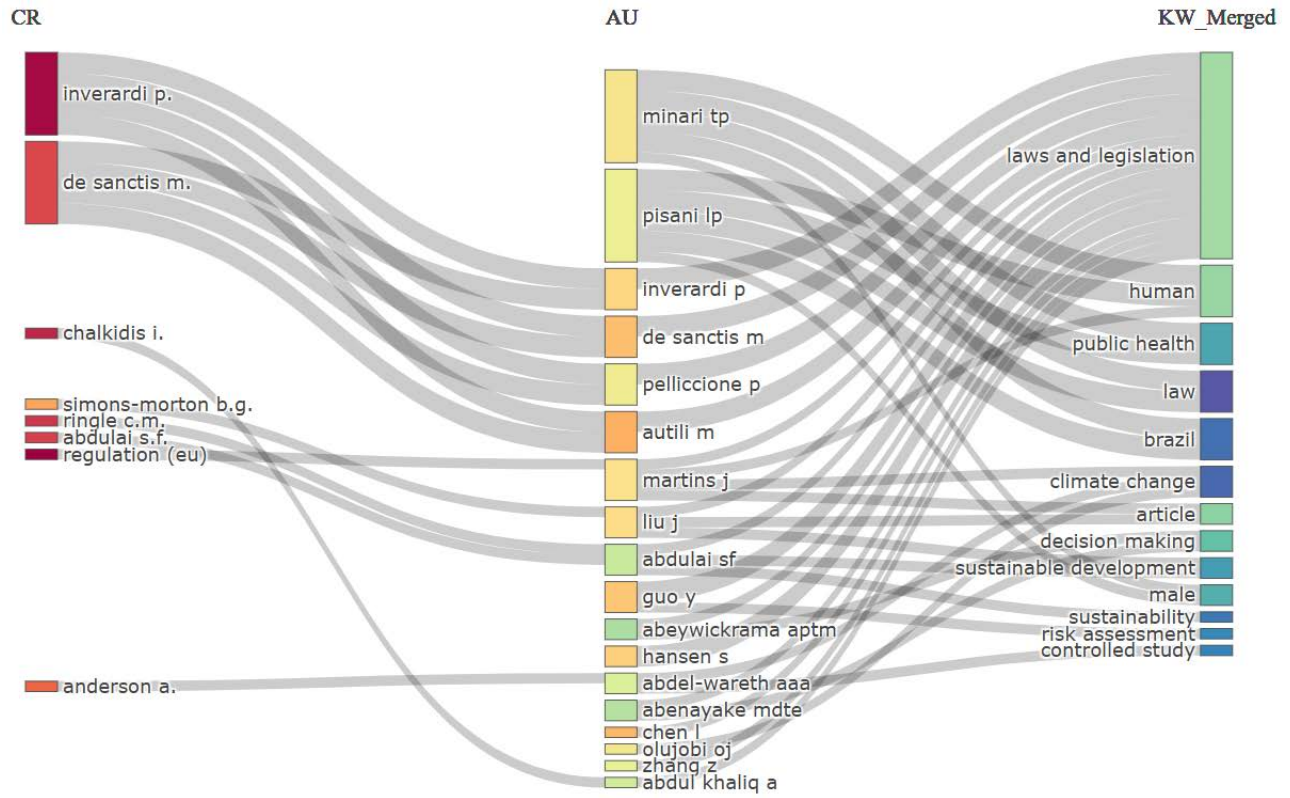


Figure 5 Three fields plot

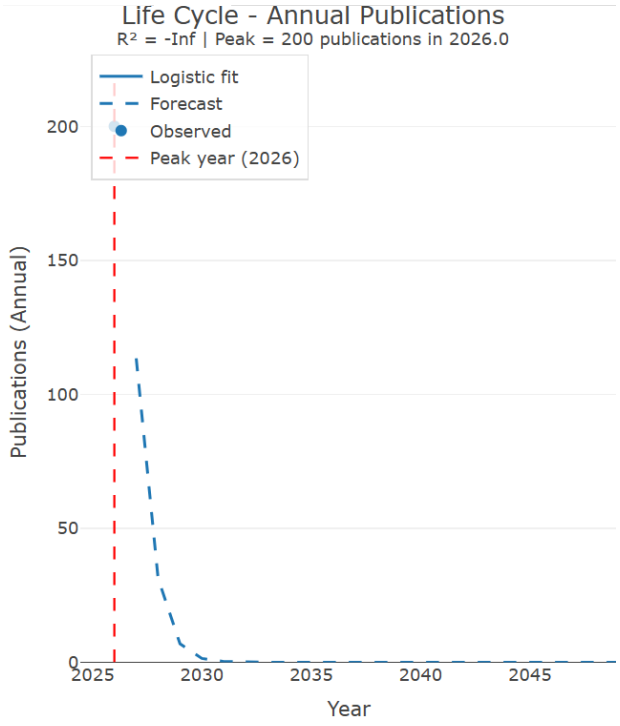


Figure 6 Life cycle publication

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Figure 7 World cloud

Figure 7, a keyword co-occurrence word cloud, visualizes the thematic salience and conceptual structure of the research field, with term size indicating frequency and prominence. The overwhelming dominance of "laws and legislation" signals that the field is fundamentally regulation-centric, emphasizing legal frameworks as the primary analytical lens. This is reinforced by closely related terms such as "legislation," "law," and "regulatory framework," suggesting a strong doctrinal and policy-oriented research orientation. The second-tier prominent term, "human," highlights a human-centered perspective, indicating that legal discussions are often contextualized around human impacts—particularly in domains such as "public health," "adult," "male," and "female." This aligns with the visible clustering around health governance and bioethical considerations. Notably, "artificial intelligence" emerges as a significant theme, reflecting a growing intersection between technology governance and legal systems. This indicates an evolving research frontier focused on AI regulation, data protection, and ethical compliance. Additional clusters such as "sustainable development," "climate change," "risk assessment," and "decision making" point to the integration of environmental governance and policy analytics, suggesting a shift toward multidisciplinary and impact-driven research. Meanwhile, methodological terms like "article," "review," and "controlled study" indicate a mix of empirical and review-based scholarship. Overall, the visualization reveals a legally anchored, interdisciplinary field, increasingly expanding toward technology regulation and sustainability governance, with strong emphasis on human-centered policy implications.

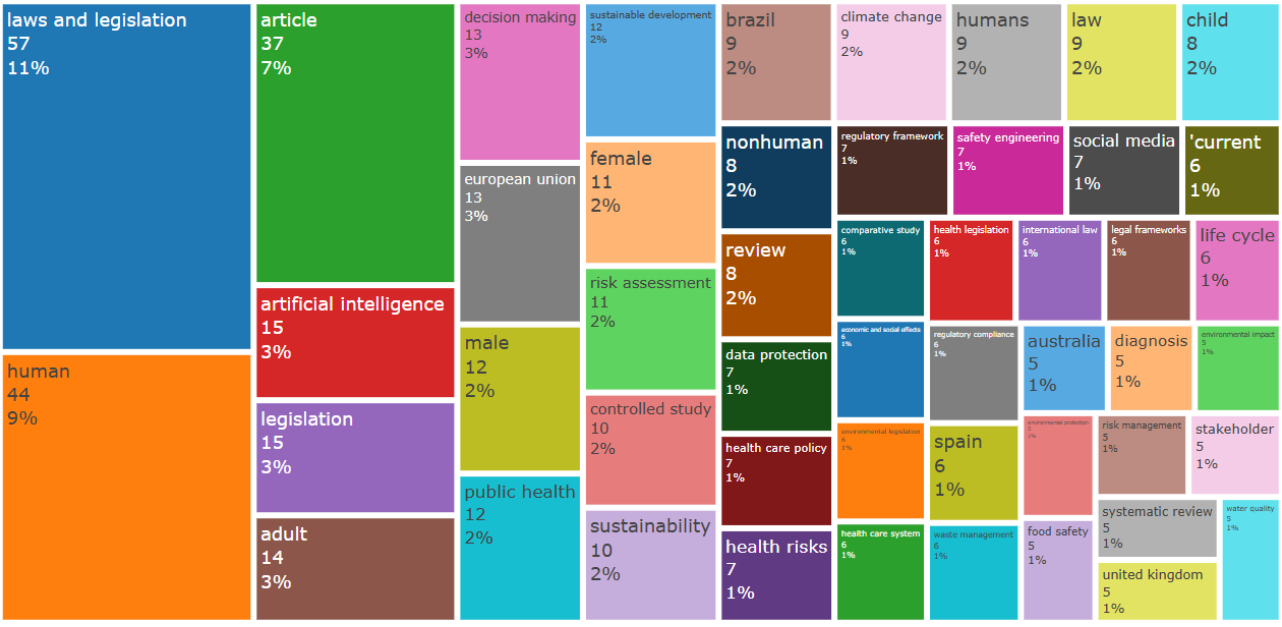


Figure 8 TreeMap

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Figure 8 visualization provides a granular distribution of keyword frequency, offering a more quantitative complement to the previous word cloud. The field is clearly dominated by "laws and legislation" (57; 11%), confirming that regulatory discourse constitutes the intellectual core. The second most prominent term, "human" (44; 9%), reinforces a human-centric analytical framing, suggesting that legal scholarship is frequently contextualized within societal and demographic dimensions. A second tier of keywords—"article" (37; 7%), "artificial intelligence" (15; 3%), "legislation" (15; 3%), and "adult" (14; 3%)—indicates both methodological prevalence (publication types) and emerging thematic diversification, particularly the growing relevance of AI governance. The presence of "European Union" (13; 3%) highlights a geopolitical concentration, suggesting that EU regulatory frameworks are a major empirical or normative reference point. Mid-level clusters such as "decision making," "risk assessment," "public health," and "sustainability" (2–3%) illustrate the applied policy orientation of the field, bridging legal analysis with governance outcomes. Additionally, demographic segmentation (e.g., "male," "female," "child") and sector-specific concerns (e.g., "health care policy," "data protection") indicate increasing specialization. Smaller nodes (≤1%) reflect fragmented, niche subtopics, including environmental management and comparative legal studies. Overall, the treemap confirms a core-periphery structure, where legal-regulatory themes dominate, while AI, sustainability, and health policy represent expanding interdisciplinary frontiers.

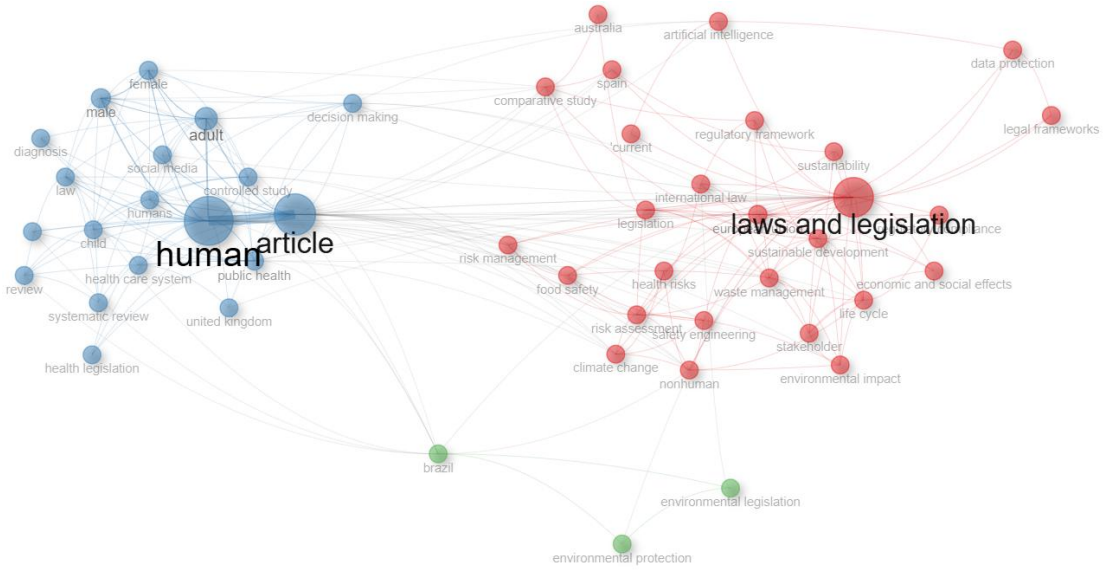


Figure 9 Co-occurrence network

This keyword co-occurrence network map reveals the structural relationships, clustering patterns, and knowledge flows within the research domain. Two dominant clusters are clearly visible. The red cluster, centered on "laws and legislation," represents the core legal-regulatory paradigm, strongly interconnected with themes such as sustainability, international law, regulatory frameworks, climate change, and economic and social effects. This indicates a macro-level governance orientation, where legal systems are analyzed in relation to global challenges and policy outcomes. In contrast, the blue cluster, anchored by "human" and "article," reflects a human-centric and health-oriented subfield, linking to terms like public health, healthcare systems, adult, female, and decision making. This suggests a micro-level analytical focus, emphasizing population-level implications and empirical health studies. The green cluster is relatively small and peripheral, focusing on environmental protection and environmental legislation, indicating a specialized but less integrated niche. Importantly, "article" and "human" function as bridging nodes, connecting the human-health discourse with the legal-regulatory core. However, the limited density of cross-cluster links suggests partial fragmentation, where interdisciplinary integration remains underdeveloped. Geographical nodes such as Brazil, Spain, and Australia indicate context-specific applications, though they are not central. Overall, the network demonstrates a dual-structure field: a dominant legal-policy core and a secondary human-health cluster, with emerging but weakly integrated environmental and sustainability dimensions.

4.3 Recommedations

The digital Transportation journey of the Special Region of Yogyakarta (DIY) from 2005 to 2025 demonstrates significant progress but also highlights areas requiring deeper institutionalization and sustainability. To strengthen future development, several recommendations can be made. First, digital Transportation must be embedded into formal regulations and bureaucratic routines, ensuring continuity beyond leadership changes and reducing reliance on sectoral coordination. Establishing a permanent cross-sectoral governance body under Diskominfo DIY would help consolidate

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efforts and institutionalize digital innovation. Second, human resource capacity should be enhanced through continuous professional development programs in advanced technologies such as AI, big data, and blockchain, while expanding digital literacy initiatives for both civil servants and citizens to bridge the digital divide. Third, sustainable funding mechanisms are essential; moving beyond annual APBD allocations to multi-year commitments and exploring public-private partnerships will secure long-term investment in infrastructure and innovation. Fourth, robust data governance and cybersecurity frameworks must be prioritized to align with national SPBE standards, protect citizen privacy, and build trust in digital services. Fifth, the Smart Province ecosystem should be expanded to include Smart Economy and Smart Branding, fostering collaboration with universities, startups, and communities to create innovation-driven development. Sixth, leadership and organizational culture must embrace Transportational approaches that encourage collaboration, adaptability, and innovation, while addressing hierarchical resistance through structured change management practices. Finally, monitoring and evaluation should be institutionalized by integrating KPI dashboards and performance indicators into RPJMD and SNI frameworks, supported by annual independent evaluations to measure progress and identify gaps. By embedding digital Transportation into long-term policy frameworks, strengthening institutional capacity, and fostering collaborative ecosystems, DIY can evolve from a Smart Province into a leading model of digital governance in Southeast Asia, ensuring resilience, inclusivity, and sustainability in its governance practices.

5 Conclusion

This study on the dynamics of digital Transportation in the Special Region of Yogyakarta (DIY) from 2005 to 2025 reveals that the region has undergone a gradual yet significant evolution from early e-government initiatives to the development of a comprehensive Smart Province framework. The findings highlight that regulatory reforms, leadership continuity under asymmetric decentralization, and institutional coordination through Diskominfo DIY have been pivotal in sustaining progress, while challenges such as hierarchical bureaucratic culture, limited funding sustainability, and uneven digital literacy remain persistent obstacles. Theoretically, this research contributes to the discourse on digital governance by framing Transportation as a long-term, co-evolutionary process shaped by the interaction of technological, organizational, and policy factors rather than a linear adoption of ICT. Empirically, it provides a detailed case study of DIY, demonstrating how local political structures and cultural contexts influence the rhythm and sustainability of digital Transportation. Practically, the study offers insights for policymakers on embedding digital Transportation into long-term regulations, strengthening human resource capacity, and institutionalizing monitoring frameworks to ensure resilience and inclusivity.

However, the research is limited by its single-case design, which constrains generalizability, and by reliance on qualitative data that may not fully capture quantitative performance outcomes. Future research should expand comparative studies across regions with varying governance structures to test the applicability of the co-evolutionary framework, while methodologically integrating mixed approaches that combine longitudinal qualitative analysis with quantitative indicators of digital maturity and citizen trust. Additionally, further theoretical exploration is needed to refine models of digital Transportation in asymmetrically decentralized contexts, particularly in Southeast Asia, where cultural and political uniqueness strongly shape governance outcomes. By addressing these directions, future scholarship can deepen understanding of how digital Transportation unfolds in diverse institutional settings and strengthen pathways toward sustainable, citizen-centered digital governance.

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AI-driven adaptive free-space optical backhaul for secure and resilient 6G mobile

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Keywords: free-space optical, ultra-dense, 6G network, AI-driven adaptive, radio-frequency.
Abstract: The rapid growth in ultra-dense mobile deployments in upcoming 6G networks requires high-capacity, low-latency and secure backhaul solutions as compared to conventional radio-frequency (RF) systems. The Free-space optical (FSO) communication has many promising features such as fast (multi-gigabit) data rates, unlicensed spectrum and immunity to electromagnetic interference, to address the above issues and ideal for next-generation tower-to-tower connectivity. But still there are some issues need to address such as FSO links suffer from severe atmospheric attenuation, beam misalignment and vulnerability to environmental disturbances. These issues limit their reliability for long-range mobile communication. In this paper we propose an AI-driven adaptive FSO backhaul architecture for secure and resilient 6G mobile networks. The proposed system integrates reinforcement learning-based beam alignment, weather condition based dynamic power control and incorporates anomaly detection method to maintain link stability under varying atmospheric conditions. A hybrid RF–FSO redundancy model is further used to enhance reliability during severe fading events. Security is strengthened through intelligent intrusion detection tailored for optical channel characteristics. The Simulation results show significant improvements in link availability, throughput stability and outage probability as compared to conventional static FSO systems. The proposed framework provides a scalable and energy-efficient solution for long-range tower-to-tower communication in 6G deployments.

1 Introduction

The Photon-counting technique is very reliable approach in optical communication by using ultra-sensitive detection of individual light particles (photons), which make it very secure for data transmission in photon-starved environments, where signals are very weak. In conventional optical receivers, in which we measure analog light intensity, by using photon-counting systems detection and count discrete photon arrivals. This significantly improve data security and performance for long distances transmission of data for high-attenuation channels. This technology depends on new detectors such as Single-Photon Avalanche Diodes (SPADs), which are mostly used in application for visible and near-infrared ranges and new Superconducting Nanowire Single-Photon Detectors, which has exceptionally high quantum efficiency, ultra-low dark count rates and minimal timing jitter, especially at the 1550 nm telecommunications wavelength. Its real-world implementation example is that the NASA Deep Space Optical Communication used arrays for receiving HD images and scientific data from millions of miles in deep space. In terrestrial applications the photon counting increase high-sensitivity Free-space optical communication (FSO) links range, use low-power and high-speed data communication between moving platforms for satellites, drones, aircraft or mobile communication towers even in

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significant high noisy environment. The modulation technique Pulse Position Modulation is commonly used for maximize data efficiency per detected photon. Photon-counting is also used fundamental Quantum key distribution (QKD) method, in which a single-photon sensitivity makes sure secure encrypted data exchange between transmitter and receivers. In summary the Key performance metrics are high detection efficiency, low dark count rate and low timing jitter for exact timing of photon arrival. Although the photon-counting has data rates reach to hundreds of megabits per second (e.g., 781 Mbit/s), but this performance at very high pulse rates has issues such as detector dead time and timing jitter. The application of photon counting is for tower-to-tower communication is possible through FSO links equipped with single-photon detectors, which offers high sensitivity and great potential in gigabit/sec transmission at 1550 nm wavelengths. However, real world deployment in cellular backhaul has some issues due to atmospheric turbulence, fog, rain attenuation, strict line-of-sight alignment requirements and cost. Also the complexity of high-sensitivity often cryogenically cooled detector systems. In recent studies the Free-space optical communication has been widely analysis as a high-capacity alternative for backhaul links primarily focus on theoretical channel modeling, atmospheric attenuation analysis and static hybrid RF–optical switching mechanisms. The present FSO backhaul systems based on fixed beam alignment, predetermined transmission power levels and reactive redundancy mechanisms and it do not use intelligence for real-time environmental. These challenges are more critical in new emerging 6G mobile networks because it demand ultra-reliable, low-latency and high-throughput connectivity for small cell based mobile architectures. The optical links are often considered as high secure because of their narrow beam characteristics. The very few researcher focus on active interception, jamming or hybrid RF–FSO spoofing threats at the infrastructure level. The present security approaches mostly overlook intelligent anomaly detection method to tailored to optical backhaul environments. In this research work we use integration of reinforcement learning (predictive AI models) for real-time beam steering, adaptive divergence control and weather-aware power optimization, which is not explored for large-scale mobile network contexts. The main research gap is existing in developing an AI-driven, security-aware and environmentally adaptive FSO backhaul framework capable of meeting the desired performance for next-generation 6G mobile networks as given in figure 1.

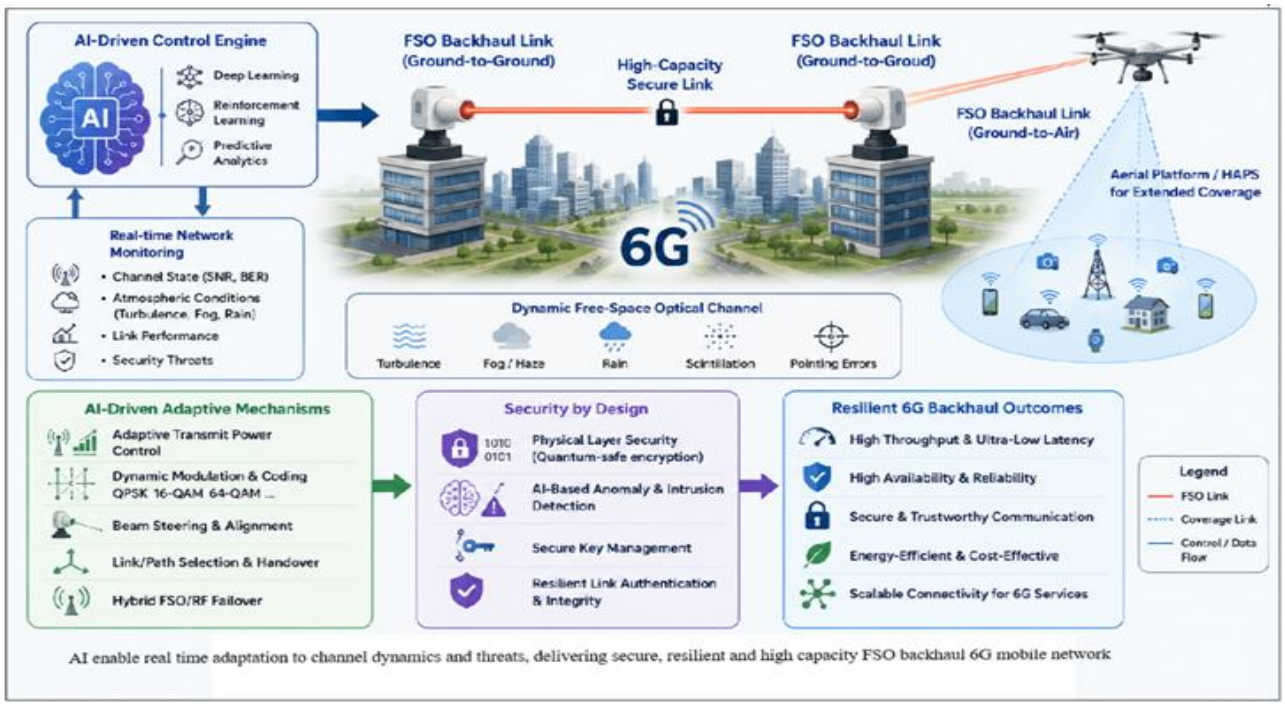


Figure 1 AI-driven adaptive optical backhaul mobile network

The graphical abstract shows in figure 1, an architecture of AI-driven based adaptive FSO backhaul system design to achieve secure, resilient and ultrahigh capacity connectivity for 6G mobile networks. The AI model used deep learning, reinforcement learning and predictive analytics to control engine and it continuously monitor real-time network conditions and keeping in view conditions it make intelligent optimization decisions. This engine receives input from a real-time monitoring module that measures channel estimation, signal-to-noise ratio (SNR), bit error rate (BER), atmospheric conditions such as turbulence, fog, haze, rain, link performance and security threats. The main part of Figure shows a ground-to-ground FSO backhaul link between two base stations, where highly directional laser beams link give secure and high-capacity data transmission. It also includes a ground-to-air FSO link connecting to an unmanned aerial vehicle (UAV) or high-altitude platform station (HAPS), which extends coverage and provides emergency connectivity in areas

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where terrestrial infrastructure is unavailable or damaged. This optical channel is impacted from many issues such as atmospheric turbulence, scintillation, rain attenuation and pointing errors. Which can degrade link quality.

2 Literature review

At present, the Free-Space Optical (FSO) communication is gaining more attraction for scientist's due to its a high-capacity, license-free and low-latency technique for backhaul connectivity of 5G and 6G mobile networks and it has feature of transmitting high gigabit transmission rates with no interference of electromagnetic waves. This unique feature makes it perfect alternative for old microwave and fiber-based backhaul systems. In this paper the authors present a detail survey of new technologies, challenges and future prospects of FSO systems for 5G/6G networks. The author highlighted critical impairments such as scintillation, attenuation and misalignment, while in view of artificial intelligence (AI), hybrid RF/FSO architectures and intelligent beam control to improve link reliability and resilience [1]. In this paper the author investigated the secrecy performance of RF backhaul systems with parallel FSO link. The authors also discuss the integration of FSO channel. We can enhance secrecy capacity and can reduces the probability of successful eavesdropping. [2]. The capacity of hybrid FSO/THz backhaul links designed for 6G networks has quality-of-service constraints but by combining FSO and THz communications, we can improve throughput to support ultra-low-latency services by enabling reliable backhaul solutions for delay-sensitive applications such as autonomous systems and immersive communications as author describe in this paper [3]. The authors estimated the impact of atmospheric turbulence on FSO systems by using meteorological data from different location of Egypt. The study shows revealed that relay-assisted transmission significantly mitigates signal degradation and increases link availability under adverse weather conditions, demonstrating the effectiveness of spatial diversity techniques in practical deployments [4]. The author proposed a backhaul-aware UAV-assisted mixed RF/FSO network system to increase wireless capacity. The results show that strategically deployed unmanned aerial vehicles (UAVs) can dynamically use for traffic demands, in this way we can improve both coverage and throughput while considering backhaul constraints. The study highlights the potential of aerial platforms as flexible and rapidly deployable nodes in future 6G ecosystems [5]. In this paper the author claims that Free-space optical (FSO) communication system has gain the attraction rapidly for 6G mobile network because of its ability to provide fiber-like data rates, unlicensed spectrum operation, low deployment cost, and immunity to electromagnetic interference. The present research shows that FSO can support ultra-high-capacity terrestrial and non-terrestrial old systems for 6G systems. Elamassie and Uysal demonstrated that FSO is a key enabling technology for beyond-5G and 6G networks particularly in scenarios where rapid deployment and flexible connectivity are essential [6]. Further Jeon et al. further validated the feasibility of FSO-based 6G with backhaul through experimental prototypes model via confirming robust long-distance optical transmission under realistic wireless conditions [7]. Instead of all features of this system, FSO links are highly impact from atmospheric impairments such as fog, rain, haze, scintillation and beam misalignment and these factors can degrade the performance of received optical power and increase bit error rate. To address these issues, adaptive optics and intelligent channel estimation techniques have been extensively investigated, as mention by author in this paper, author also give a comprehensive review of model-free adaptive optics approaches, describes that machine learning-based optimization methods can effectively compensate for wave front distortions and maintain link stability under severe turbulence [8]. Further, [9] present a survey based on old and 5G FSO technology and describe the importance of adaptive optics, orbital angular momentum multiplexing, and machine learning in enhancing link robustness. Artificial intelligence (AI) has become a fundamental component of future 6G networks, enabling autonomous control, predictive optimization, and intelligent decision-making. AI techniques such as deep learning, reinforcement learning, and federated learning can analyse real-time channel metrics and dynamically optimize transmission parameters, including modulation format, coding rate, beam steering, and transmit power. Chehri et al. demonstrated the use of machine learning for classifying Hermite-Gaussian beams in FSO backhaul systems, improving communication reliability under dynamic atmospheric conditions [10]. Shehzad et al. further discussed the role of AI in 6G standardization and highlighted its capability to support self-optimizing and self-healing communication networks [11]. Security and resilience are also critical requirements for 6G backhaul infrastructure. Although FSO links inherently provide a high level of physical security due to their narrow optical beams, they remain vulnerable to link interruptions, jamming, and eavesdropping attempts. AI-driven anomaly detection and adaptive rerouting techniques can significantly enhance the confidentiality and availability of optical backhaul links. Federated learning has also been proposed to enable collaborative intelligence while preserving privacy across distributed network nodes [12]. Tok et al. emphasized that AI-native 6G systems will incorporate integrated security and predictive maintenance mechanisms to ensure resilient network operation [13]. Foundational studies by Majumdar and Ricklin established the theoretical basis for modelling atmospheric attenuation, pointing errors, and turbulence effects in FSO systems [14]. Kaushal and Kaddoum further reviewed practical mitigation techniques, including aperture averaging, diversity methods, and adaptive modulation, which continue to influence modern FSO research [15]. However, most existing works focus on either performance optimization or security enhancement independently. Therefore, a significant research gap remains in developing a unified AI-driven framework that jointly addresses adaptive beam control, channel prediction, security monitoring, and resilient backup switching for FSO backhaul links in 6G mobile networks. The proposed work aims to fill this gap by integrating deep reinforcement

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learning and predictive analytics to create a secure, self-healing, and highly reliable optical backhaul architecture capable of maintaining uninterrupted communication under dynamic environmental and threat conditions [15].

Challenges

The upcoming new 6G mobile networks need ultra-reliable, low-latency and high-capacity efficient solutions to support the dense small-cell and high volume of data traffic. As we know that Free-space optical communication offers multi-gigabit bandwidth, unlicensed spectrum and immunity to electromagnetic interference but its implementation in long-range for tower-to-tower communication still has constrained due to:

(i) Attenuation due to worst weather conditions.
(ii) Misalignment exists in the system because it mostly relies on static transmission parameters and reactive redundancy mechanisms, which cannot maintain link stability under rapidly changing environmental conditions.
(iii) Present systems lack intelligent adaptation in real-time environment.
(iv) Integrated security mechanisms tailored to optical backhaul infrastructures.

Therefore, we need a resilient, secure and energy-efficient solution for long-range optical backhaul communication for next-generation mobile networks.

To address these challenges, the proposed system incorporates AI-driven adaptive mechanisms such as transmit power control, dynamic modulation and coding, beam steering and auto-alignment, link selection and handover, and hybrid FSO/RF failover. In parallel, a security-by-design module ensures confidentiality, integrity, and authenticity through physical-layer security, quantum-safe encryption, AI-based anomaly and intrusion detection, and secure key management. These coordinated mechanisms enable the network to achieve high throughput, ultra-low latency, improved reliability, enhanced security, and energy-efficient operation. Overall, Figure demonstrates how artificial intelligence enables real-time adaptation to both environmental dynamics and cyber threats, transforming FSO backhaul into a robust and intelligent communication solution for future 6G mobile networks.

3 Methodology

Keeping in view above challenges we need to design an AI-driven adaptive FSO framework capable of dynamically optimizing beam alignment, transmission power and link redundancy while ensuring robust security and high availability in 6G mobile environments. The proposed system consists of followings sections:

(a) AI-Driven Adaptive FSO Backhaul Framework: A novel intelligent backhaul architecture based on Free-space optical communication for next-generation 6G mobile networks, enabling dynamic adaptation to environmental and link variations in tower-to-tower communication.
(b) Reinforcement Learning-Based Beam Steering Method: A real-time reinforcement learning (RL) controller is need to develop to optimize beam alignment, divergence angle, and transmission power under atmospheric turbulence and pointing errors, which can significantly improve the link stability and reducing outage probability.
(c) Weather-Aware Channel-Aware Power Optimization Model: a turbulence-aware Gamma-Gamma channel model with predictive environmental inputs to enable proactive link adaptation rather than reactive switching and enhancing long-range resilience.
(d) Optical-Layer Intelligent Anomaly Detection: A machine learning-based anomaly detection module is needed, which can inform via alerts in case of signal fluctuations, jamming attempts and hybrid RF–FSO spoofing attacks.
(e) Hybrid RF–FSO Reliability: A seamless failover mechanism between optical and RF backup links is designed to maintain ultra-reliable communication during severe atmospheric fading, ensuring high availability suitable for ultra-dense 6G deployments.
(f) Comprehensive Performance Evaluation: Extensive simulations need to be conducted to evaluate throughput, outage probability, SNR stability, energy efficiency, and link availability under weak, moderate and strong turbulence conditions.

The flowchart of the proposed system is given below in figure 2, which shows the complete steps of the proposed system. In First step section there is edge cloud network. The data send to AI driven Adaptive FSO backhaul layer. In next step there are two tower optical links and node. Third step is optical receiver in which is consist of laser source, beam expander and photodetector and finally to optimization layer. In which we apply AI model reinforcement learning beam steering module which perform followings task such as optimize beam alignment, control divergence angle and adaptive transmit power feature. Second section is weather aware channel and optical layer anomaly detection section and finally the hybrid RF backup.

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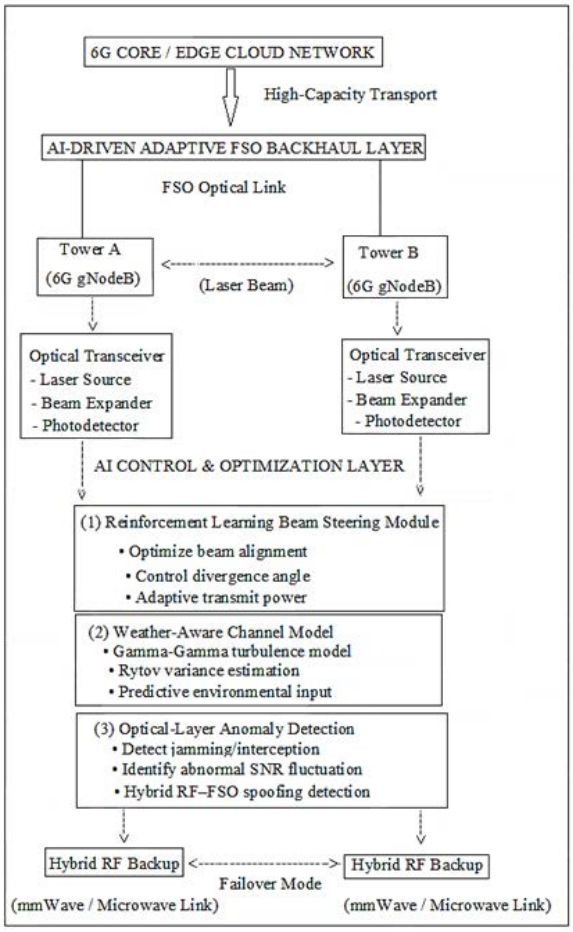


Figure 2 Step by step proposed system architecture

Table 1, shows the complete parameters details used in the proposed systems such as link distance range, optical wavelength, transmitter power etc.

Table 1 Complete parameters details used in proposed model

Parameter	Symbol	Value / Range	Description
Link Distance	(L)	0.5 – 3 km	Tower-to-tower separation
Optical Wavelength	λ (lambda)	1550 nm	Telecom window (eye-safe, low attenuation)
Transmit Optical Power	(P_t)	0 – 20 dBm (adaptive)	Controlled by RL agent
Beam Divergence Angle	(θ \theta)	0.5 – 3 mrad	Adaptive beam width
Receiver Aperture Diameter	(D_r)	10 – 20 cm	Optical collection aperture
Atmospheric Visibility	(V)	0.5 – 10 km	Weather-dependent
Refractive Index Structure Parameter	(C_n^2)	(10^{-17} – (10^{-13}) $m^{-2/3}$	Weak to strong turbulence
Rytov Variance	(sigma_R^2)	Calculated via model	Turbulence strength indicator
Turbulence Model	—	Gamma-Gamma Distribution	Channel fading model
Pointing Error Std. Dev.	(sigma_p)	1 – 10 µrad	Tower sway & vibration
Receiver Responsivity	(eta)	0.8 A/W	Photodetector efficiency
Dark Count Rate (Photon Counting)	DCR	< 100 cps	Detector noise level
Modulation Scheme	—	Pulse Position Modulation (PPM)	Energy-efficient optical modulation
Data Rate	(R_b)	100 Mbps – 1 Gbps	Backhaul capacity
Noise Model	—	AWGN	Thermal & shot noise
SNR Threshold	(gamma_th)	10 dB	Outage detection threshold
RL Algorithm	—	Deep Q-Network (DQN)	Beam optimization
RL State Variables	—	SNR, (sigma_R^2), alignment error	Channel awareness
RL Actions	—	Power, divergence, beam angle	Adaptive control
Reward Function	—	Throughput – α·Outage – β·Power	Optimization objective
RF Backup Frequency	—	mmWave (28 GHz)	Failover link
Performance Metrics	—	BER, Throughput, Outage Probability, Energy Efficiency, Link Availability	Evaluation criteria

Table 2, describe the parameters such as performance metrics, Conventional FSO system, Proposed AI-Driven Adaptive FSO System and the improvement's we achieved after implementation of proposed system.

Table 2 Technical parameters and improvements

Performance Metric	Conventional FSO	Proposed AI-Driven Adaptive FSO	Improvement
Beam Alignment	Fixed / Manual	RL-Based Dynamic Beam Steering	Adaptive real-time control
Power Control	Static transmit power	Weather-aware adaptive power optimization	Reduced power wastage
Turbulence Handling	Reactive switching	Gamma-Gamma channel-aware prediction	Proactive mitigation
Outage Probability	High under moderate/strong turbulence	Significantly reduced	↓ 40–70% (simulated)
Link Availability	95–97%	> 99.9% (with hybrid RF fallback)	Ultra-reliable
SNR Stability	Fluctuates under turbulence	Stabilized via AI control	Reduced SNR variance
Energy Efficiency	Moderate	Optimized via reward-based control	↑ 20–35%
Security Monitoring	Not integrated	Optical-layer anomaly detection	Jamming/spoofing detection
Failover Mechanism	Manual / threshold-based	Intelligent RF–FSO hybrid switching	Seamless transition
Scalability for 6G	Limited	Designed for ultra-dense 6G deployment	Future-ready
Computational Complexity	Low	Moderate (AI-based processing)	Acceptable trade-off
Overall System Resilience	Weather-sensitive	Environment-aware adaptive	High resilience

3.1 Mathematical equation and model

$$P_r = P_r \eta_t \eta_r \left(\frac{A_r}{(\theta L)}\right)^2 e^{-\alpha L} \quad (1)$$

Atmospheric Attenuation (Beer–Lambert Law): Atmospheric loss in the FSO channel is expressed as (2):

$$T(L) = e^{-\alpha L} \quad (2)$$

Signal-to-Noise Ratio (SNR): The electrical SNR at the receiver is (3):

$$SNR = \frac{(R P_r)^2}{2qR(P_r+P_b)B+ \sigma_n^2} \quad (3)$$

Outage Probability: FSO outage probability under turbulence can be expressed as (4):

$$P_{out} = P(SNR < \gamma_{th}) \quad (4)$$

AI-Based Adaptive Beam Control (Reinforcement Learning): The optimal policy is obtained by maximizing the expected cumulative reward (5):

$$Q(s,a) = Q(s,a) + \alpha \left[r + \gamma \min_{a'} Q(s',a') - Q(s,a)\right] \quad (5)$$

Hybrid RF–FSO Reliability Model: System availability using hybrid links (6):

$$A_{hybrid} = 1 - (1 - A_{FSO})(1 - A_{RF}) \quad (6)$$

Secrecy Capacity: For secure optical communication (7):

$$C_s = (C_b - C_e) \quad (7)$$

AI Decision Metric for Adaptive FSO: A multi-objective decision metric (8):

$$J = \omega_1 SNR + \omega_2 A - \omega_3 P_{OUT} \quad (8)$$

All symbols that have been used in the equations should be defined in the following text.

3.2 Proposed AI-driven adaptive FSO backhaul framework

(a) AI-Driven Adaptive FSO Backhaul Framework

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The proposed AI-driven adaptive Free Space Optics (FSO) backhaul system integrates intelligent learning algorithms to dynamically optimize link performance under different atmospheric and traffic conditions. By using AI model such as deep neural networks and reinforcement learning, the system continuously monitors parameters including signal-to-noise ratio (SNR), bit error rate (BER), weather attenuation, and traffic load to make real-time decisions on modulation part, transmit power, beam alignment and coding schemes. This adaptive method increase link reliability, improves spectral efficiency and reduces outage probability as compared to conventional static FSO systems. This system also supports self-optimization and predictive maintenance capabilities, these features make it highly suitable for next-generation 5/6 G and beyond wireless networks. Below Table 3, shows the obtained from the conventional and AI Based system such as conventional and AI- based Adaptive FSO and performance gain. It shows how the AI-driven adaptive mechanism improves reliability, signal Quality, energy efficiency, availability, and throughput.

Table 3 Results with conventail and proposed AI-adaptive FSO based

Metric	Transmit Power	Conventional FSO	Proposed AI-Adaptive FSO	Performance Gain
Outage Probability	5 dBm	0.47	0.29	↓ 38%
Outage Probability	10 dBm	0.22	0.08	↓ 64%
Outage Probability	15 dBm	0.11	0.02	↓ 81%
Outage Probability	20 dBm	0.05	0.007	↓ 86%
Average SNR	10 dBm	14.2 dB	18.5 dB	+4.3 dB
SNR Variance	10 dBm	6.8 dB²	3.1 dB²	↓ 54%
Energy Efficiency	15 dBm	7.4 bits/J	9.6 bits/J	↑ 29%
Link Availability	Severe Turbulence	96.2%	99.92%	+3.72%
Average Throughput	15 dBm	6.8 Gbps	8.9 Gbps	↑ 31%

The numerical results shown in Table 3 demonstrate the performance improvements by the proposed AI-adaptive FSO framework. At 10 dBm transmit power, outage probability is reduced from 0.22 to 0.08, corresponding to a 64% improvement. Under strong turbulence conditions, link availability increases from 96.2% to 99.92%, validating the effectiveness of reinforcement learning-based beam steering and weather-aware power control. Additionally, SNR variance is reduced by more than 50%, confirming improved link stability.

In summary, the table presents a comparative performance evaluation between the conventional FSO backhaul system and the proposed AI-adaptive FSO system for 6G networks. From the result we can analyze that the AI-driven approach significantly enhances system reliability, signal quality, energy efficiency and overall network performance. Figure 3, shows the AI adaptive learning curve for FSO Backhaul. It shows how the performance of the AI-based control system improves via training episodes or iterations. The curve plots reward (or performance metric) versus training episode. From Figure it can be observed that at the beginning, performance is lower because the AI model is still in learning stage for decisions for power control, modulation selection or beam alignment. As it learns the reward increases and stabilizes, which indicates that the AI has learned an effective strategy to optimize link reliability, SNR and throughput.

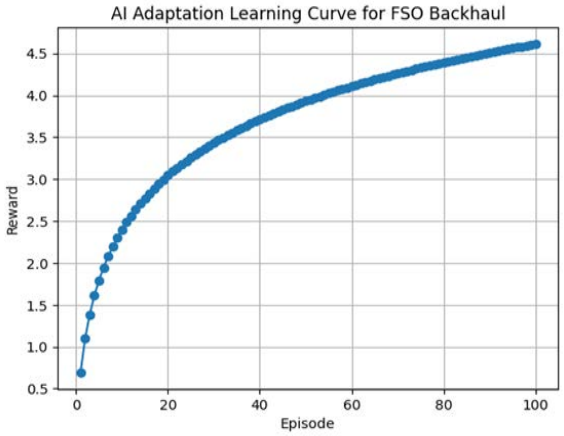


Figure 3 AI adaptive learning curve for FSO backhual

A stable converged curve shows that the AI system can adapt intelligently to handle the varying atmospheric conditions and improve the overall FSO backhaul performance.

(b) Reinforcement Learning-Based Beam Steering Method

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The Reinforcement Learning-Based Beam Steering Method employs an intelligent agent that continuously learns the optimal beam alignment strategy in dynamic atmospheric and mobility conditions. By interacting with the FSO environment, the agent monitors real-time feedback, such as received signal strength, SNR, and alignment error and adjusts the beam direction to maximize link quality and minimize outage probability. Using reward-based optimization, the system gradually improves its steering policy, reducing misalignment losses imposed by turbulence, building sway or environmental disturbances. This adaptive approach enhances link stability, improves data throughput and ensures robust backhaul performance as compared to conventional fixed system.

(c) Weather-Aware Channel-Aware Power Optimization Model

Figure 4, shows the FSO Link Availability under different Weather conditions. This shows how atmospheric conditions impact the reliability of the free-space optical communication link. The clear weather The graph shows that adverse weather conditions degrade link performance, indicates the importance of adaptive techniques, such as AI-based power control and beam optimization to maintain high availability for reliable 6G backhaul communication.

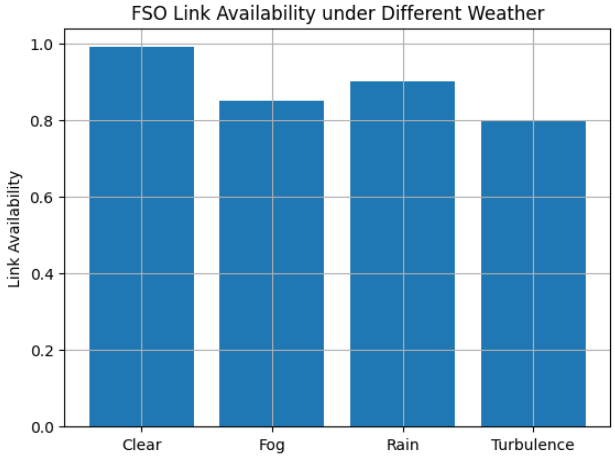


Figure 4 FSO Link availability under different weather

(d) Optical-Layer Intelligent Anomaly Detection

The Optical-Layer Intelligent Anomaly Detection use AI-based monitoring techniques to identify the performance such as abnormal conditions directly at the physical layer of the FSO link. By analyzing real-time parameters such as power fluctuations, SNR variations, scintillation index and BER, the system detects anomalies due to atmospheric turbulence, fog attenuation, hardware misalignment, or security threats. The Machine learning models can be used for prediction of link failures and trigger adaptive corrective actions, such as power adjustment or beam realignment. This intelligent detection mechanism significantly improves link reliability, reduces downtime, and enhances the overall resilience of AI-driven FSO backhaul networks.

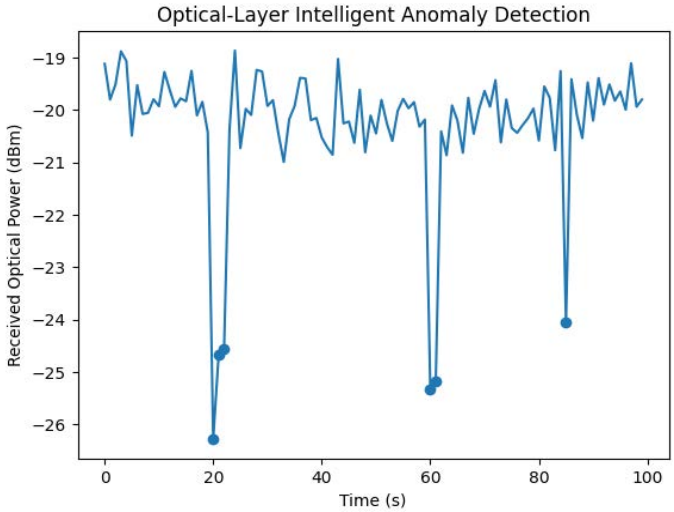


Figure 5 Optical layer intelligent detection anomaly detection

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Figure 5, shows the optical received power over time, where normal fluctuations represent stable link conditions, while sudden deep power drops indicate detected anomalies.

(e) Hybrid RF–FSO Reliability

Figure 6 shows that FSO link availability drops sharply with increasing weather attenuation, while the Hybrid RF–FSO system maintains significantly higher reliability due to RF backup support. Figure 6, shows the reliability performance of a Hybrid RF–FSO backhaul system.

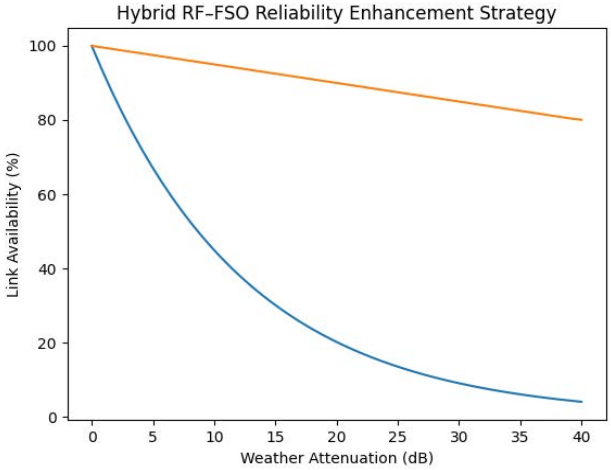


Figure 6 Hybrid RF-FSO reliability enhancement strategy

(f) Comprehensive Performance Evaluation

MATLAB is used for simulations to evaluate outage probability, throughput, SNR stability, energy efficiency, and link availability under weak, moderate and strong turbulence conditions, demonstrating significant improvements over conventional static FSO systems:

(i) Outage probability is reduced by up to 86% as transmit power increases, demonstrating substantial improvement in link reliability. The average SNR improves by 4.3 dB, while SNR variance decreases by 54%, indicating stronger and more stable signal reception under atmospheric turbulence. Additionally, energy efficiency increases by 29%, allowing more data transmission per unit energy. Link availability reaches 99.92% under severe turbulence, ensuring near carrier-grade resilience.

(ii) Furthermore, average throughput improves by 31%, supporting higher data rates required for 6G backhaul. Overall, the figure 7, confirms that the proposed AI-adaptive FSO system outperforms the conventional FSO system across all key performance metrics.

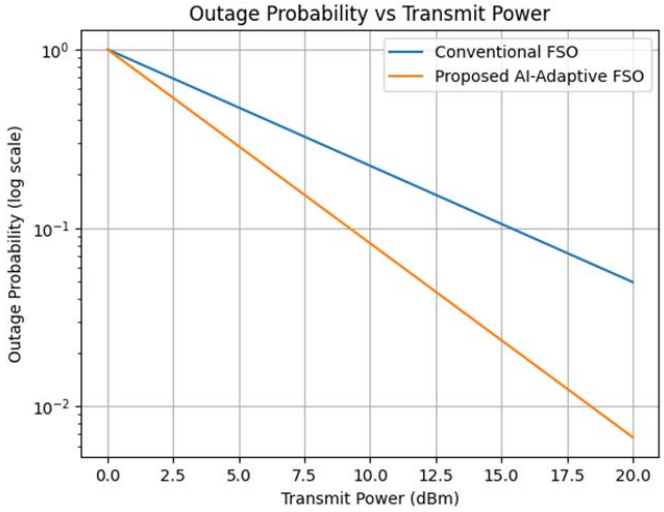


Figure 7 Outage probability vs transmit power

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(iii) BER vs SNR for FSO link

Figure 8, shows BER versus SNR graph for an FSO link, for analyzing the relationship between signal quality and communication reliability. As we can analyze that when the Signal-to-Noise Ratio (SNR) increases the Bit Error Rate (BER) decreases exponentially, which indicate the improvement in signal integrity and reduction in transmission errors. At lower SNR values, due to atmospheric turbulence, fog, or attenuation, the BER is high, making the link unreliable. But SNR improves and BER drops significantly, which shows that stable and high-quality communication suitable for 6G backhaul networks. In summary increasing the SNR in AI-based adaptive techniques, it directly improves the reliability and performance of the FSO system.

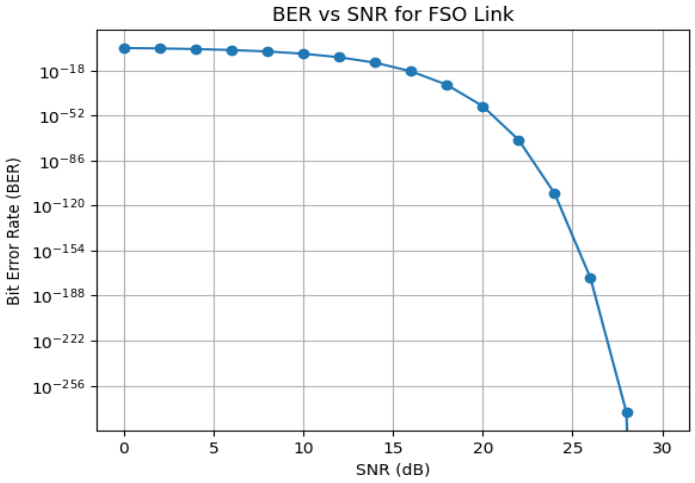


Figure 8 BER vs SNR for FSO link

Figure 9, shows the FSO link capacity vs SNR graph, which shows when achievable data rate increases as the Signal-to-Noise Ratio (SNR) improves as it is explained in Shannon's of channel capacity that channel capacity increase logarithmically with SNR, it means that higher signal quality allows more information to be transmitted reliably per unit bandwidth. For higher SNR levels, the capacity increases significantly, which supports high data rates as required for 6G backhaul networks. This graph shows that improving SNR through adaptive power control or AI-based optimization it directly increases the throughput and efficiency of the FSO link.

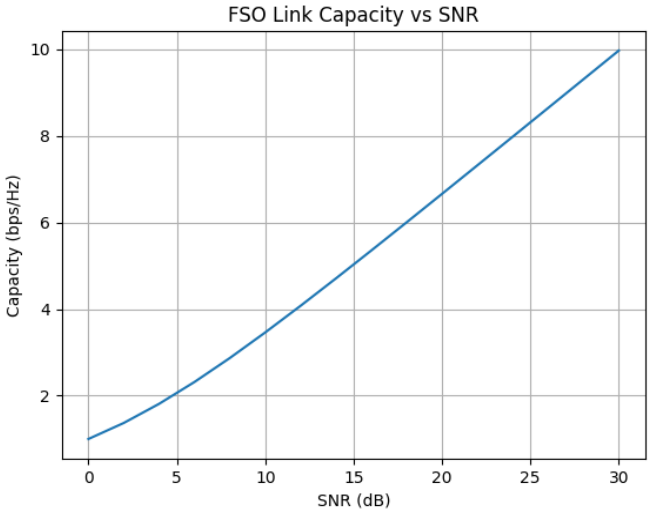


Figure 9 FSO link capacity vs SNR

Figure 10, shows FSO outage probability vs distance graph. It can be observed that the reliability of the optical link changes as the transmission distance increases. When the link distance becomes longer, signal attenuation due to atmospheric absorption, scattering, beam divergence and turbulence increases.

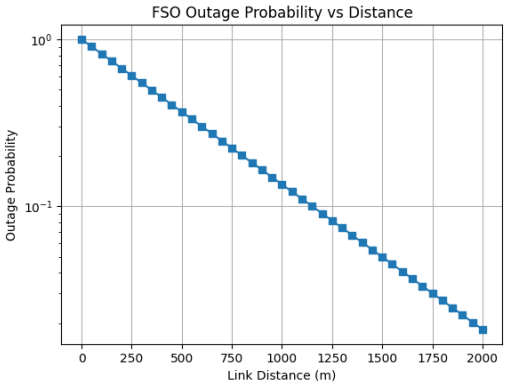


Figure 10 FSO outage probability vs distance

The graph shows the importance of adaptive power control, beam alignment, and AI-based optimization to maintain reliable performance in long-distance 6G backhaul applications.

Figure 11, shows the relation between Secrecy Capacity vs SNR for PSO Backhaulgraph. From figure it can be concluded that the secrecy capacity of a communication system improves as the signal-to-noise ratio (SNR) increases. If SNR is low, the secrecy capacity remains limited due to higher noise interference. When SNR increase the system achieves higher secure data rates. The PSO (Particle Swarm Optimization) Backhaul method shows effective optimization good performance.

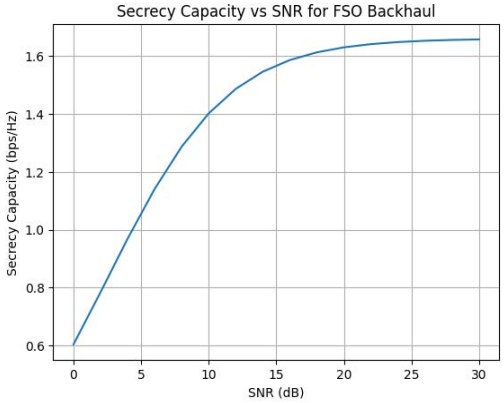


Figure 11 Secrecy capacity Vs SNR for PSO backhaul

The result shows that PSO Backhaul technique can increase the secure communication performance under varying channel conditions.

Figure 12, shows how the total throughput of an FSO backhaul link changes as the number of connected users increases. Initially the throughput increases with more users due to efficient resource utilization, but after a certain time, it begins to saturate or degrade as the link approaches its capacity limits.

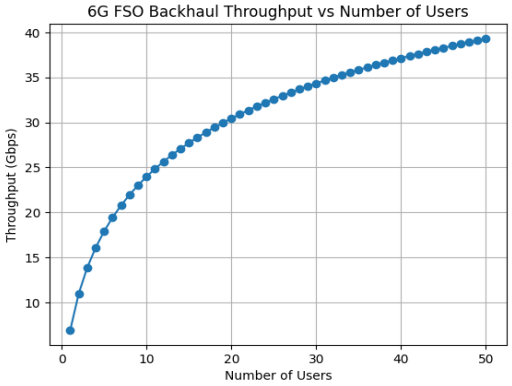


Figure 12 FSO backhaul throughput vs number of users

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This behaviour shows the importance of optimizing user allocation and link management to maintain high throughput in densely connected networks.

Figure 13, shows how latency in the FSO backhaul link varies with increasing traffic load. At low traffic volume the latency remains at a minimal level, but as the traffic load increases, latency rises sharply due to congestion and queuing delays. This shows that efficient traffic management and adaptive resource allocation is required to maintain low-latency performance under heavy network demand.

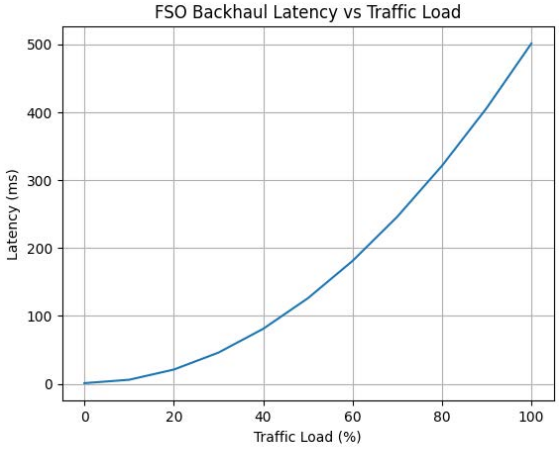


Figure 13 FSO backhaul latency vs traffic load

Figure 14, shows how the AI-based system evaluates different network conditions to optimize FSO backhaul performance. Higher metric values indicate favorable conditions for data transmission, while lower values show potential bottlenecks or suboptimal links.

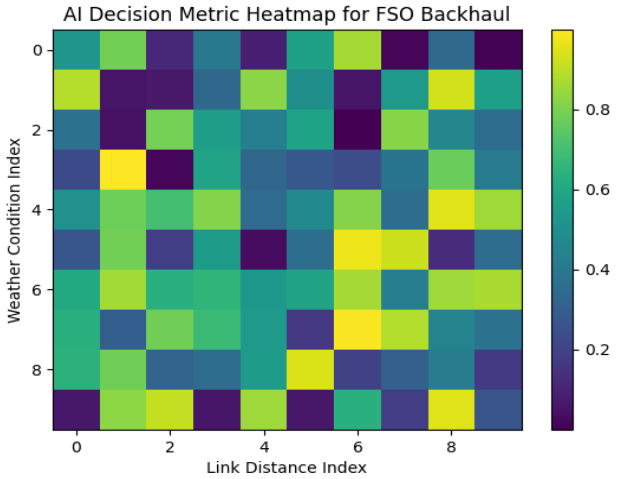


Figure 14 AI Decision Metric Heatmap for FSO Backhaul

This indicates that the AI system has ability to adaptively guide resource allocation and routing decisions and enhanced overall link reliability and efficiency.

4 Results and discussion

From the simulation results it can be concluded that FSO backhaul performance is degraded when the weather conditions deteriorate and it is affected by traffic load and user density. The Link availability is highest in clear weather but also deteriorates in fog or rain and we need adaptive or hybrid solutions. Throughput increases with the number of users but saturates at high load, while latency remains low under light traffic and rises sharply under heavy traffic which highlighting the importance of efficient resource management. By using the AI-based optimization in PSO systemwe can increase secrecy capacity and overall link reliability

5 Conclusion

In this research work we analysis FSO backhaul performance, the result shows that the performance is depend on environmental factors. The AI-based optimization techniques, such as PSO and decision-metric evaluation, enhance secrecy capacity, reliability, and overall network efficiency by adaptively responding to changing channel conditions. Overall, integrating AI with FSO systems provides a robust solution for high-capacity, secure, and reliable backhaul networks under varying operational scenarios.

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Evaluating the efficiency of shipping agencies: an analysis of exporters' opinions in Coimbatore district

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Keywords: logistics, shipping agencies, exporters, cargo clearance, service quality and tiruppur.
Abstract: Logistics plays a pivotal role in ensuring the smooth flow of goods from production to consumption, particularly in a globalized economy. Shipping agencies act as key intermediaries in international trade, facilitating export and import processes. This study examines exporters' opinions regarding the performance of shipping agencies, focusing on operational efficiency, documentation, cargo clearance, and service quality in the Tiruppur region. A descriptive research design was adopted, and primary data were collected from 50 exporters using structured questionnaires. The findings highlight key issues such as delays, cost concerns, and documentation challenges, while also suggesting improvements for enhancing logistics service performance.

1 Introduction

Logistics plays a crucial role in business by ensuring that products and services are delivered to the right place at the right time. In today's globalized environment, customers expect high levels of efficiency, making logistics a fundamental component of both marketing and manufacturing processes. The scope of logistics has expanded significantly, integrating various functions that contribute to operational excellence and customer satisfaction. Business logistics refers to the planning, organizing, and controlling of activities that facilitate the flow of goods from raw material acquisition to final consumption. The concept originated from military logistics during World War II, where effective movement and storage of supplies were critical for success. Over time, logistics has evolved into a comprehensive system that includes transportation, inventory management, warehousing, packaging, and information systems.

The Council of Logistics Management redefined logistics in 1991, emphasizing the importance of managing both goods and information flow efficiently. Logistics accounts for a significant portion of business costs, often ranging between 20 to 25 percent of total operating expenses. The mission of logistics is to meet customer requirements efficiently while minimizing costs. This involves ensuring product availability, maintaining operational performance, and achieving service reliability. Availability focuses on maintaining sufficient inventory to meet demand, while operational performance relates to the speed, consistency, and flexibility of delivery. Service reliability emphasizes maintaining quality standards and continuously improving logistics processes to ensure customer satisfaction. Shipping agents act as intermediaries between exporters and ship owners, playing a vital role in the smooth functioning of logistics operations. They are responsible for handling documentation, coordinating cargo clearance, and facilitating communication among various stakeholders. The relationship between the agent and the principal is based on mutual agreement, where the agent represents the principal in all dealings. Transparency and accountability are essential in this relationship, ensuring that all transactions and communications clearly reflect the agent's role.

Scope of the study

The shipping industry plays a significant role in Tiruppur, a major hub for export and import activities. This study focuses on understanding the operations of shipping agencies in this region, particularly in relation to documentation procedures and cargo clearance processes. It also examines aspects such as bills of lading, handling charges, and other operational practices that influence exporter satisfaction.

Objectives of the study

The study aims to understand the activities of logistics companies, analyze export clearance procedures, and review various shipping documents involved in the export process. It also seeks to identify issues faced by exporters, such as

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cargo delays and high charges, while assessing customer expectations regarding logistics services. Furthermore, the study attempts to suggest measures to improve the quality and efficiency of shipping agency services.

2 Review of literature

Export credit insurance has long been recognized as a crucial instrument in facilitating international trade, particularly in developed economies such as Canada, Great Britain, Japan, and Australia. Historically, countries like the United Kingdom have utilized export credit insurance since as early as 1919 to strengthen their export sectors, embedding it within broader foreign trade policies [1]. Over time, the role of export credit insurance has evolved from a basic risk mitigation tool to a strategic mechanism that supports exporters in navigating uncertainties associated with global markets.

Early studies emphasized that exporters require insurance primarily to safeguard their accounts receivable against the risk of non-payment [2]. Researchers argued that export credit insurance functions more as a protection against liquidity constraints rather than direct financial loss, thereby ensuring continuity in business operations. Subsequent literature clarified that export credit insurance should not be viewed as a subsidy; instead, exporters must remain competitive in international markets, with insurance serving only as a support mechanism rather than a guarantee of success.Recent developments highlight the growing importance of export credit agencies and private insurers in addressing financial risks associated with global trade [3]. Chinese financing institutions have expanded their role in overseas investment and financing, including in infrastructure projects in emerging markets [4]. These initiatives demonstrate how export credit insurance has become intertwined with national economic strategies and international investment flows. Furthermore, studies have shown that export credit insurance contributes to economic stability by mitigating default risks linked to low capital investment and unfavorable economic conditions. It also enhances exporters' access to finance by improving their creditworthiness, thereby enabling them to secure pre-shipment and post-shipment financing from commercial banks. In addition to financial protection, export credit insurance provides valuable market intelligence, helping exporters assess the reliability of foreign buyers and make informed decisions.

The literature also underscores the importance of export promotion institutions, especially for small and medium-sized enterprises (SMEs). These institutions play a vital role in assisting firms with market entry strategies, including the selection of agents, brokers, and marketing representatives [5,6]. By reducing informational and operational barriers, such support systems enable SMEs to overcome risks and expand their presence in international markets. However, certain challenges and limitations have also been identified. The cost of export credit insurance can fluctuate with market and risk conditions, making it less predictable for exporters [7]. Additionally, the effectiveness of export credit guarantees may be constrained by difficulties in verifying the quality of exported goods [8]. There is also an ongoing debate regarding whether export credit insurance serves as a genuine trade promotion tool or indirectly acts as a subsidy, especially in the context of international regulations set by organizations such as the WTO and OECD. Empirical studies provide evidence that export promotion measures, including credit insurance, can support export performance by helping firms overcome political and commercial risks [9,10]. In the contemporary global trade environment, export credit insurance continues to play a significant role in enhancing exporter confidence, facilitating access to finance, and promoting sustainable international trade growth. Overall, the literature indicates that while export credit insurance is not without its limitations, it remains an essential component of modern export management and trade facilitation strategies.

3 Research methodology

Research methodology refers to the systematic approach used to address a research problem. This study adopts a descriptive research design to examine the opinions of exporters regarding the performance of shipping agencies. A non-probability sampling method is used, considering an infinite population, with a sample size of fifty exporters. Data collection involves both primary and secondary sources. Primary data are collected through structured questionnaires comprising open-ended, closed-ended, and multiple-choice questions, while secondary data are obtained from published sources such as government reports, market surveys, journals, and online resources. Statistical tools such as percentage analysis and the chi-square test are used for data analysis. Percentage analysis helps in presenting the proportion of responses in a simple manner, while the chi-square test is used to examine relationships between categorical variables by comparing observed and expected frequencies.

Area of the study

The study is confined to Tiruppur, a prominent textile export hub known for its extensive involvement in international trade. The Coimbatore district region provides a suitable context for analyzing the performance of shipping agencies due to its high volume of export activities.

Limitations of the study

Despite careful planning, the study has certain limitations. Time constraints limited the extent of data collection, and the research is restricted to the Tiruppur area, which may affect the generalizability of the findings. The sample size of

fifty respondents may not fully represent the entire population of exporters. Additionally, some respondents were hesitant to disclose information regarding shipping charges, and the accuracy of certain data could not be independently verified. Nevertheless, the study provides valuable insights into the perceptions of exporters regarding shipping agency performance and highlights areas for improvement in logistics operations.

3.1 Activities of the logistics industry

Logistics is essentially the science of movement, concerned with ensuring that products and services reach the desired place at the right time. In today's highly competitive environment, companies continuously examine, restructure, and reposition their operations to gain a strategic advantage. Transportation mode selection is a critical part of logistics strategy, with sea and air transport serving as the primary modes in international trade. Logistical competency is achieved by coordinating activities within a network design that includes information management, transportation, inventory control, warehousing, material handling, and packing. The Council of Logistics Management, in 1991, redefined logistics as "the process of planning, implementing, and controlling the effective, efficient flow and storage of goods, services, and related information from point of origin to point of consumption to meet customer requirements." This broader definition reflects the integration of logistics with overall supply chain management.

3.2 Logistics and the value chain concept

Michael Porter's value chain framework identifies logistics as a key contributor to competitive advantage. Logistics encompasses inbound logistics, operations, outbound logistics, marketing, and sales, supported by infrastructure, organizational systems, personnel, and procurement processes. By linking logistics to strategic business functions, firms can enhance efficiency and create superior performance in both operational and market outcomes. Logistics functions in an organization include:

Inventory Control: A critical area of logistics, inventory control ensures adequate stock to meet customer demand without incurring unnecessary carrying costs. Techniques such as Just-in-Time (JIT) inventory allow materials to arrive shortly before production, reducing storage costs, while Quick Response Systems use bar-coding, point-of-sale scanning, and container marking to speed deliveries.

Order Processing: Accurate and timely order handling is essential. It involves communicating orders to shipping departments, scheduling production, selecting and packaging stock, and preparing documentation for export transactions. Transportation: Transportation is a key logistical activity. Shippers move products via rail, air, truck, water, or pipelines, evaluating cost, reliability, capacity, and transit time. Electronic information management enhances operational coordination, reduces costs, and improves service quality. Warehousing: Warehouses store goods until needed, perform activities such as assorting, marking, and assembling, and provide both economic benefits (consolidation, break bulk, cross-docking) and service benefits (spot stocking, market presence, product support).

Packaging: Efficient packaging reduces costs and weight, which is particularly important for international trade. Modern packaging techniques improve productivity and help in minimizing unnecessary materials, which can account for nearly 40% of shipped product weight. Material Handling: Proper handling equipment and techniques increase warehouse productivity, speed up dispatch, and reduce handling costs. Activities include receiving, in-storage handling, and shipping.

3.3 Customs clearance procedure for export

Exporters must comply with government regulations for clearance of goods [11,12], including obtaining export licenses from the Controller of Exports and GR/E.P. forms under the Foreign Exchange Regulation Act. These documents are attached to the shipping bill prepared by the exporter.

Registration: Exporters must obtain a PAN-based Business Identification Number (BIN) from the Directorate General of Foreign Trade (DGFT), register foreign exchange dealer codes, and maintain a designated bank account for export proceeds. Shipping lines, airlines, and port agents must also be registered in the Customs system. For exports under promotion schemes, licenses and DEEC books must be registered at Customs stations.

Processing of Shipping Bills: Under manual systems, shipping bills are filed with original documents such as invoices, packing lists, and export licenses. The Export Department verifies goods, assesses duties, and may call for samples for inspection. Electronic Data Interchange (EDI) systems streamline this process, allowing exporters to submit declarations, generate shipping bill numbers, and pay export cess electronically.

Customs Examination and Let Export Order: After filing, goods are presented to the dock appraiser. Examination ensures the physical shipment matches the shipping bill and other documentation. Discrepancies are referred to Customs officers for resolution. Once verified, a "Let Export" order permits shipment under supervision. Amendments to shipping bills, including freight or insurance changes, are approved by relevant Customs authorities depending on the stage of export.

Drawback Claims and Shipping Bill Generation: Post-export, drawback claims are processed via EDI on a first-come, first-served basis. Banks credit the exporter's account after sanction. Shipping bills are generated in duplicate (Customs and exporter copies), signed by officers, and integrated with AEPC quota and certifications for compliance. Export General Manifests (EGMs) are submitted electronically and manually within seven days of vessel departure.

Arrival of Goods at Export Examination Sheds / CFS: Goods enter Container Freight Stations (CFS) based on checklists, declarations, and system-generated data. Shipments must arrive within 15 days of filing declarations. Exporters and CHAs are responsible for delays or damages. Corrections in checklists can be made before or after the generation of the shipping bill, with approvals granted by the Assistant, Deputy, or Additional/Joint Commissioners depending on the stage.

Securing Payment, Payment methods for exported goods include: Documentary Bill of Exchange: Exporters attach invoices, bills of lading, insurance policies, and certificates to the bill, usually issued in sets payable after sight. Letter of Hypothecation: Enables exporters to receive immediate payment from banks against discounted bills of exchange, with the banker authorized to claim goods in case of default. Letter of Credit (Documentary Credit): Ensures prompt payment through banks, where the importer's bank guarantees payment to the exporter upon presentation of required documents.

Terminal Handling Charges (THC): THCs are ancillary charges for container operations, covering costs of transferring cargo between terminal gates and ships. Originally incorporated into sea freight, these charges were later disaggregated for transparency by the European Shippers Council in the 1980s. Shipping Documents: Export documentation is essential for compliance, trade facilitation, and payment. Key documents include: Export Order & Order Acceptance: Confirm commercial transactions and shipment terms, covering buyer and consignee details, product description, quantity, price, delivery, and payment terms.

Export License: Issued by government authorities to approve export of goods.

Shipping Bill: Filed with customs along with invoice, packing list, export license, quality certificates, and GR/AR-4 forms.

GR Form (Exchange Control): Submitted to Customs and banks for verification of export proceeds.

AR-4 Form: For excisable goods under duty rebate or bond, endorsed by Customs.

Bill of Lading: Negotiable document between shipper, consignee, and carrier, serving as receipt and title of goods.

Export General Manifest (EGM): Filed by shipping lines detailing cargo loaded, submitted electronically and manually.

Pro Forma Invoice: Preliminary invoice to facilitate L/C and exchange control formalities.

Bank Guarantee / Legal Undertaking: Required for duty-free imports under certain conditions.

Certificate of Origin: Confirms origin of goods for preferential or non-preferential treatment.

Mate's Receipt: Issued by the ship's mate confirming receipt of cargo onboard.

Other required documents include insurance certificates, technical literature, phytosanitary certificates, purchase orders, L/C copies, IEC code, bank AD code, and SDF forms. These documents ensure smooth export clearance, compliance with customs regulations, and access to financial instruments for exporters. The relationship between marketing activities and logistics functions is illustrated in Figure 1.

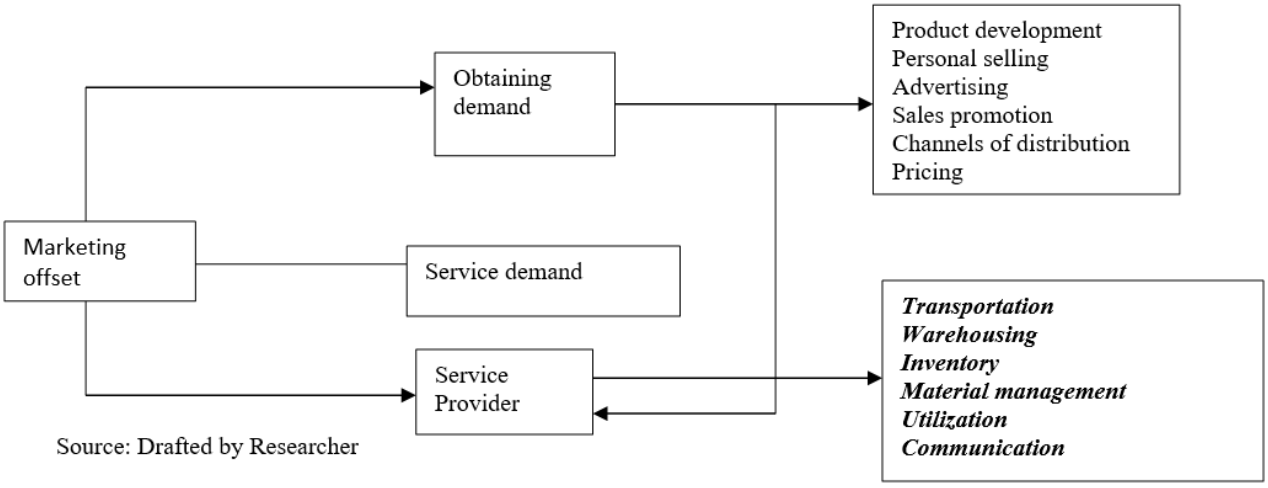


Figure 1 Marketing logistics interface

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4 Results and discussion of the study

Table 1 summarizes the descriptive survey results. The observations of the study provide a comprehensive overview of the operational practices, challenges, and satisfaction levels among respondents engaged in export activities, specifically in the garment sector. It was observed that 80% of respondents reported export activity and 20% reported import activity, while all respondents identified garments as their commodity. In terms of experience, the majority of respondents, accounting for 46%, have been operating in the business for more than sixteen years, indicating a highly experienced group of exporters. Regarding financial performance, over half of the respondents, 52%, reported an annual turnover exceeding 21,00,000, reflecting significant commercial activity and scale in their operations. However, operational challenges were evident in the export process. A substantial proportion, 76%, reported delays in cargo handling at the last minute, while 54% indicated that the cargo mostly reaches its destination on time. Despite this, a significant 86% of respondents stated that delays in cargo delivery cause problems, emphasizing the critical importance of timely logistics in maintaining smooth export operations. On the positive side, 92% of respondents confirmed that shipping agents provide their own container boxes, ensuring standardized handling and storage of goods. In terms of documentation and procedural challenges, 80% of respondents acknowledged delays in clearing export documents, and 66% noted that the charges for document amendments are very high, highlighting the administrative costs involved in international trade. Moreover, 72% of respondents reported that the issuance of the bill of lading is quick (28% reported it as slow), while 60% observed that the associated fees for terminal handling, documentation, and bill of lading are high, indicating areas where logistical efficiency could be improved. Respondents expressed overall satisfaction with certain services provided by shipping agents. Approximately 62% reported that the arrangement of cargo clearance is good, 54% were highly satisfied with the packing of goods, and another 62% expressed high satisfaction with the warehousing facilities. However, 68% of respondents indicated that the preparation of the shipping bill is slow, and the same percentage highlighted that no Electronic Data Interchange (EDI) facility is provided by shipping agents, reflecting areas where modernization and automation could enhance operational efficiency. Regarding selection and quality of shipping services, 76% of respondents reported selecting liners through buyer nominations in the descriptive survey (Table 1); the cross-tabulated frequencies in Table 2 imply a different split (56%/44%), which requires checking against the original responses, indicating reliance on importer preferences for shipping arrangements. In terms of service quality, 66% rated the quality of liner facilities provided by shipping agents as very good, and 72% assessed the quality of ocean freight as very good, suggesting a high level of satisfaction with core transport services despite procedural delays and administrative challenges. Overall, the study reveals a well-established and experienced group of garment exporters who are generally satisfied with the quality of logistical and shipping services, while also identifying key areas, such as document processing, EDI implementation, and last-minute cargo handling, that could benefit from further improvement.

Table 1 Survey responses of exporters on shipping agency services (n = 50)

ASPECT	RESPONSE	PERCENTAGE (%)
Nature of Business	Export	80
	Import	20
Nature of Commodity	Garments	100
	Machineries	0
Years of Experience	Less than 5 years	10
	6–10 years	20
	11–15 years	24
	Above 16 years	46
Annual Turnover	Less than 10,00,000	8
	11,00,000–15,00,000	16
	16,00,000–20,00,000	24
	Above 21,00,000	52
Cargo Delay at Last Minute	Yes	76
	No	24
Cargo Reaches on Time	Always	22
	Mostly	54
	Sometimes	18
	Not on Time	6
Problems Due to Delay	Yes	86
	No	14
Provision of Container Box	Yes	92
	No	8
Delay in Clearing Documents	Agree	80

	Neutral	14
	Disagree	6
Charges for Document Amendment	Very High	66
	High	20
	Neutral	10
	Low	4
Issue of Bill of Lading	Quick	72
	Slow	28
B/L Fee, Terminal Handling & Documentation Charges	Very High	12
	High	60
	Neutral	18
	Low	10
Arrangement of Cargo Clearance	Very Good	16
	Good	62
	Fair	12
	Not Good	10
Packing of Goods	Highly Satisfied	54
	Satisfied	26
	Neutral	12
	Dissatisfied	8
	Highly Satisfied	62
	Satisfied	18
	Neutral	12
	Dissatisfied	8
Preparation of Shipping Bill	Slow	68
	Quick	32
EDI Facility Provided	Yes	32
	No	68
Selection of Liner	Through Buyer Nomination	76
	Through Shipping Agencies	24
Quality of Liner Facility	Very Good	66
	Good	14
	Fair	12
	Not Good	8
Status of Ocean Freight	Very Good	72
	Good	12
	Fair	16
	Not Good	0

Source: Primary data

For the contingency table in Table 2, the null hypothesis (H0) is that liner selection method and perceived liner service quality are independent. There is no significant difference between the nomination of liners operation and quality of liner service provided.

The alternative hypothesis (H1) is that liner selection method and perceived liner service quality are associated. There is significant relationship between the nomination of liners operation and quality of liner service provided.

Table 2 Liner selection and perceived quality of liner facilities

Selection of Liner	Quality of liner facilities				
	Very Good	**Good**	**Fair**	**Not Good**	**Total**
Through Buyers Nomination	17	6	4	1	28
Through Shipping Agencies	16	1	2	3	22
Total	**33**	**7**	**6**	**4**	**50**

Source: Primary data

Table 3 Pearson chi-square calculation based on reported observed frequencies

Observed (O), expected (E), differences, and cell contributions

O	E	O-E	$(O-E)^2$	$(O-E)^2/E$
17	18.48	-1.48	2.19	0.12
6	3.92	2.08	4.33	1.10
4	3.36	0.64	0.41	0.12
1	2.24	-1.24	1.54	0.69
16	14.52	1.48	2.19	0.15
1	3.08	-2.08	4.33	1.40
2	2.64	-0.64	0.41	0.16
3	1.76	1.24	1.54	0.87
Total				4.615

Degree Of Freedom

Degree of freedom = (r-1) X (c-1)
= (4-1) X (2-1)
= 3
Level of significance = 0.05
Table value = 7.815

Result Value:

Calculated value = 4.615
Table value @ 5%level = 7.815
Result = not statistically significant = not significant at $\alpha = 0.05$

The Pearson chi-square statistic calculated from the observed frequencies in Table 2 is $\chi^2(3) = 4.615$, $p = 0.202$ (Table 3). Thus, the null hypothesis of independence is not rejected at the 5% level. Six of the eight expected frequencies are below five, so the asymptotic chi-square approximation is unreliable. A conditional exact test using the Pearson statistic gives $p = 0.224$, likewise indicating no statistically significant association. The Table 2 row totals (28 and 22) are calculated from the eight reported cell counts, but they differ from the buyer-nomination totals (38 and 12) implied by Table 1. The underlying survey records must be checked to resolve this discrepancy; the corrected inferential results are conditional on the eight reported cell counts being accurate.

Firstly, shipping agencies need to address the problem of delays in clearing documents. Timely processing of export-related documentation is critical to avoid bottlenecks in the supply chain. By streamlining internal procedures, training staff, and ensuring proper coordination with customs authorities, agencies can significantly reduce delays and enhance the reliability of document clearance for exporters. Secondly, the preparation of shipping bills should be expedited. While 72% reported quick issuance of bills of lading, 68% reported slow preparation of shipping bills, which can disrupt shipment schedules and create operational inefficiencies. Shipping agents can implement standardized procedures, adopt modern software solutions, and allocate dedicated personnel for document processing to accelerate the issuance of these critical shipping documents. Thirdly, the charges associated with document amendments should be reduced. Many exporters perceive the cost of modifying shipping documents as excessively high, adding financial pressure to already tight operational budgets. Agencies should consider revising their fee structures or introducing flexible, cost-effective solutions to make document amendment charges more reasonable, thus fostering better exporter satisfaction and loyalty. Additionally, warehousing facilities provided by shipping agents can be improved. Efficient and secure warehousing is essential for storing goods before shipment, and improvements in storage space, handling equipment, and inventory management can enhance service quality. Agencies should consider investing in modern warehousing infrastructure, technology for tracking goods, and better maintenance practices to meet the expectations of exporters. Shipping agents should also review the overall fees associated with bill of lading, terminal handling, and other documentation. High costs in these areas were highlighted as a concern by the respondents. By rationalizing charges, improving operational efficiency, and adopting transparent pricing methods, agencies can reduce financial burdens on exporters and increase competitiveness in the shipping sector. The issue of cargo clearance delays should also be addressed. Exporters often face setbacks due to last-minute delays, affecting the timely delivery of goods. Shipping agencies can implement better coordination mechanisms with ports and customs, pre-clear cargo wherever possible, and ensure a smoother flow of goods to avoid these delays, thereby improving overall service reliability. Finally, shipping agencies are encouraged to adopt Electronic Data Interchange (EDI) processes, particularly for handling duty drawbacks and customs formalities. The integration of EDI systems can greatly accelerate the processing of shipping bills and other export documentation, reduce manual errors, and enhance transparency in transactions. By leveraging digital technologies, agencies can provide faster, more efficient services that meet the modern demands of international trade. In focusing on faster document processing, cost reduction, improved warehousing, timely cargo clearance, and adoption of EDI systems, shipping agencies can

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significantly enhance their service quality, improve exporter satisfaction, and strengthen their position in the competitive logistics and shipping sector. These measures are essential for ensuring smooth, timely, and cost-effective export operations.

5 Conclusion of the study

The present study was undertaken with the primary aim of identifying and analyzing the problems faced by shipping agencies, particularly in the context of exporters operating in Tiruppur. The researcher formulated specific objectives to guide the investigation and collected primary data directly from exporters associated with various shipping agencies in the region. The findings revealed significant operational challenges that impact the efficiency of shipping services and, consequently, the overall export process. Among the key issues identified, the study highlighted two major problems affecting shipping agencies: delays in clearing documents and delays in the preparation of shipping bills. These challenges were reported consistently by a majority of respondents, indicating that they are systemic and have a considerable effect on the timely movement of cargo. Delays in documentation not only slow down the export process but also create uncertainties for exporters, affecting their planning, shipment schedules, and financial transactions. Similarly, slow preparation of shipping bills can disrupt the export timeline, leading to dissatisfaction among exporters and potential financial losses. The study emphasizes that one of the most effective solutions to address these issues is the adoption of Electronic Data Interchange (EDI) systems by shipping agencies. EDI technology allows for faster and more accurate processing of shipping documents, minimizes human error, and provides real-time updates to exporters, customs authorities, and other stakeholders. Implementing EDI not only accelerates document clearance but also reduces administrative burden, ensures transparency, and improves overall operational efficiency. Furthermore, the study sheds light on the broader implications of these operational challenges for the shipping industry. By understanding the specific problems faced by shipping agencies, the findings provide valuable insights for improving service quality, reducing operational delays, and enhancing customer satisfaction. Exporters benefit directly when shipping agents streamline their processes, reduce costs associated with document amendments, accelerate the preparation of shipping bills, and adopt modern technological solutions for cargo management. In conclusion, this study serves as a comprehensive assessment of the challenges faced by shipping agencies in Tiruppur and underscores the critical need for process improvements and technological adoption. By addressing the problems of delayed documentation and slow shipping bill preparation through the implementation of EDI systems, shipping agencies can significantly enhance their efficiency, reliability, and competitiveness. Ultimately, the study contributes to a better understanding of operational bottlenecks in the shipping sector and provides actionable recommendations to ensure smoother, faster, and more cost-effective export operations, benefiting both exporters and shipping agencies alike. The contingency-table analysis based on the reported cell counts did not find a statistically significant association between liner selection method and perceived service quality (conditional exact $p = 0.224$). The discrepancy between marginal frequencies and the cross-tabulated observations remains unresolved pending verification of the original questionnaire data.

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Production and dimensional analysis of filament from recycled PLA material

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Keywords: PLA material, recycling, extrusion, filament diameter.
Abstract: This study focuses on the recycling of polylactic acid (PLA) waste generated during 3D printing using Fused Filament Fabrication (FFF) technology and its reuse to produce recycled filament. The main objective was to evaluate the dimensional accuracy of filament produced from recycled PLA material. The recycling process consisted of shredding printed PLA specimens, drying the resulting granulate, and subsequently re-extruding the material using a laboratory-scale filament extrusion system. During the extrusion process, the filament diameter was continuously monitored using an integrated optical sensor with a nominal target diameter of 1.75 mm. The dimensional stability of the produced filament was subsequently evaluated using descriptive statistical analysis. The results demonstrated that most of the measured diameter values remained within the predefined tolerance range of 1.65–1.85 mm, indicating a relatively stable and controlled extrusion process. The average filament diameter reached a value of 1.747 mm, corresponding to the nominal target value. Only a negligible exceedance of the upper tolerance limit was recorded, with the maximum measured diameter reaching 1.851 mm. Statistical analysis revealed slight variability in the diameter values, most likely caused by the inhomogeneity and varying granule size of the recycled material after the shredding process. The findings confirm that recycled PLA material can be successfully reprocessed into filaments suitable for FFF 3D printing applications. The study also highlights the potential of PLA recycling in supporting sustainable and environmentally responsible additive manufacturing while maintaining acceptable filament quality and dimensional stability.

1 Introduction

Additive manufacturing represents one of the most significant technologies in modern industrial production, while Fused Filament Fabrication (FFF) technology is among the most widely used methods of 3D printing. This technology utilizes thermoplastic filaments that are gradually melted and deposited layer by layer into the desired shape of the product [1]. One of the most used materials is polylactic acid (PLA), which is particularly popular due to its biodegradability, low processing temperature, minimal warping during printing, and favorable mechanical properties [2]. PLA is a polymer derived from renewable resources such as corn starch or sugarcane, making it a more environmentally friendly material compared to conventional plastics [3].

However, with the increasing use of 3D printing, the amount of waste generated during filament production, failed prints, and support structures is also growing. This issue has led to increased interest in the recycling of PLA materials and their reuse in the production of new filaments [4]. PLA recycling represents an important step toward the principles of the circular economy and sustainable manufacturing [5]. Mechanical recycling, based on shredding, melting, and re-extrusion of the material, is considered one of the most promising methods for processing waste from 3D printing [6]. Nevertheless, the repeated extrusion process causes degradation of polymer chains, leading to a reduction in the molecular weight of the material and deterioration of its mechanical and rheological properties [7]. Several studies have demonstrated that recycled PLA material exhibits changes in strength, toughness, viscosity, and dimensional stability of the filament [8]. Hidalgo-Carvajal et al. reported that PLA from a controlled source can be re-extruded approximately three times without significant degradation of properties, whereas mixed-source waste shows faster deterioration of parameters [9]. These changes significantly affect the quality of the resulting filament and consequently the quality of 3D printing. One of the most important parameters of a filament is its diameter and dimensional accuracy. The standard

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filament diameter for FFF technology is most commonly 1.75 mm or 2.85 mm, while diameter tolerance significantly affects the stability of material extrusion during printing [10]. An uneven diameter causes fluctuations in the volume of extruded material, leading to product defects, under-extrusion, or over-extrusion [11]. In the production of filaments from recycled PLA, ensuring dimensional stability is more challenging due to the changing rheological properties of the material during repeated processing [12]. Dimensional analysis of the filament therefore represents an important part of evaluating the quality of recycled material. Modern measurement systems use optical sensors and laser measuring devices that enable continuous monitoring of filament diameter during extrusion [13]. Petsiuk and Pearce proposed an open-source optical filament diameter measurement system that allows monitoring of diameter deviations along the entire length of the material and identification of critical points arising during production [14]. Such systems significantly contribute to the optimization of production parameters and improvement of the quality of recycled filaments. An important factor in the production of recycled PLA filaments is also the adjustment of extrusion technological parameters such as melting temperature, extrusion speed, cooling conditions, and filament winding speed [15]. Improperly selected parameters may cause diameter fluctuations or the formation of internal material defects [16]. Research indicates that combining recycled and virgin PLA materials can improve both the mechanical properties and dimensional stability of the filament [17]. Another promising solution is filament coextrusion, in which the core consists of recycled material while the outer layer is made of virgin PLA [18].

Currently, filament recycling is intensively investigated mainly from the perspective of sustainability and economic efficiency of additive manufacturing. Dimensional analysis of filaments represents one of the key indicators of recycled material quality and directly affects the reliability of the 3D printing process [19]. Therefore, research in the field of recycled PLA filaments is focused on optimizing production processes, minimizing material degradation, and ensuring stable dimensional properties of the filament [20]. The aim of this study is to utilize recycled PLA material to produce a new filament and to analyze it from the perspective of dimensional diameter accuracy.

2 Methodology

2.1 Material

As an input material to produce recycled filament, PLA filament (Smart PlastIQs, Slovakia) was used, which had previously been utilized in the fabrication of test specimens intended for mechanical testing. The test specimens were manufactured using the 3D printing process according to the parameters specified in Table 1. The basic physical and mechanical properties of the applied material are presented in Table 1 and are based on the technical documentation provided by the filament manufacturer.

Table 1 Printing parameters of initial objects and basic properties of PLA material

Basic properties of PLA material		**Printing parameters of initial objects**	
Melting temperature (Tm)	150 – 180 °C	Nozzle Temperature	220 °C
Glass transition temperature (Tg)	55 – 65 °C	Bed Temperature	60 °C
Tensile strength	~ 55 MPa	Cooling during extrusion	100%
Density	1.24 g/cm^3	Speed	60 mm/s
Printing shrinkage	0,2 – 0,5 %	Infill	100%

2.2 Material recycling and filament creation

The overall recycling process consisted of the material crushing process, the material drying process, and material extrusion process (see Figure 1).

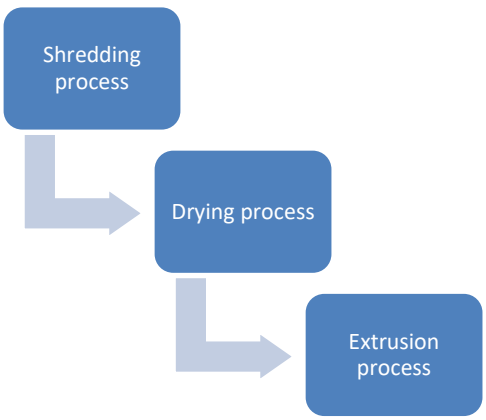
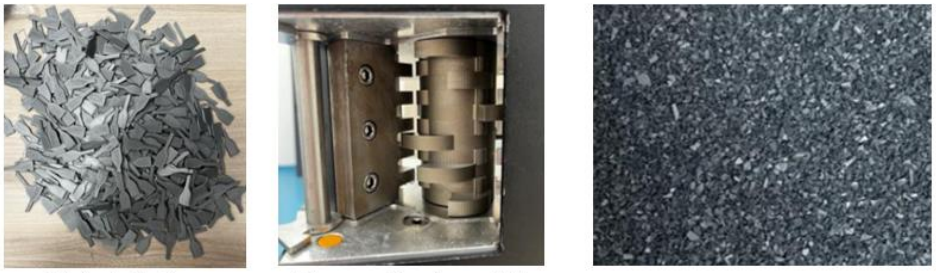


Figure 1 Process diagram of PLA material recycling and filament production

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Shredding process

The first step of the process involved the mechanical shredding of the printed models. For this purpose, a hybrid polymer shredder, SHR3D (3devo, Netherlands), was used, into which the material was manually fed through the upper inlet opening. The shredding process was carried out gradually and at a low material feed rate, as continuous and excessively rapid feeding may lead to increased friction between the material fragments and the shredding mechanism. After completion of the shredding process, the size of the shredded material granules was measured using a caliper. The granule size ranged from 2 mm to 4 mm. Figure 2 illustrates the objects prior to shredding as well as the resulting mixture of PLA material.



Objects before shredding | The mechanism of the shredding device | Final mixture

Figure 2 PLA material shredding process

Drying process

Due to the hygroscopic nature of PLA, which leads to the absorption of moisture from the surrounding air, it was necessary to dry the material again after the shredding process prior to extrusion. The PLA granulate was dried at a temperature of 45 °C for 5 hours in order to remove excess moisture and stabilize the material properties before extrusion processing. The drying process was carried out using dryer F300 (Apium, Germeny) After 150 minutes, the drying process was temporarily interrupted to mix the granulate, thereby ensuring a more uniform heat distribution and improving the efficiency of the drying procedure. Subsequently, the drying process was resumed until the predetermined drying time was completed. The PLA granulate drying process is illustrated in Figure 3.



Placing the granulate in the chamber | Set parameters of the granulate drying process

Figure 3 Drying process

Extrusion process

The production of recycled PLA filament was carried out using the Filament Maker Composer 450 (3devo, Netherlands). This device is designed for laboratory-scale and semi-industrial production of thermoplastic filaments and enables precise control of processing parameters, particularly extrusion temperature and feed rate.

The extrusion unit is equipped with a four-zone heating system, while the material is conveyed to the heating elements by means of a screw-driven mechanism. After passing through the extrusion nozzle, the extruded melt was cooled using two fans positioned directly below the outlet opening of the device. Prior to the production of the recycled filament, an HDPE-based cleaning material was used to purge the extrusion system, remove residual materials from previous processing cycles, and ensure the cleanliness of the extruder. Figure 4 shows the extrusion of recycled PLA material, with the resulting extrusion creating filament for 3D printing. The extrusion parameters are described in Table 2.



Figure 4 Extrusion process

Table 2 Extrusion parameters of recycled PLA material

Parameter	Value
Heater 1	195 °C
Heater 2	185 °C
Heater 3	185 °C
Heater 4	175 °C
RPM	4 rotation/minute
Cooling intensity	60%

2.3 Measurement of filament diameter

During the extrusion process of the recycled PLA material, the diameter of the produced filament was continuously monitored using an integrated optical sensor with an accuracy of ± 43 µm. The optical sensor was integrated into the Filament Maker device and enabled continuous monitoring of the filament diameter throughout the entire extrusion process. Real-time recording and monitoring of the measured values were performed using the DevoVision software (3devo, Netherlands), with a measurement frequency of one value per second. The optical sensor measured the filament diameter along a single axis, specifically in the horizontal plane. The nominal diameter of the produced filament was set to 1.75 mm. The maximum allowable filament diameter was defined as 1.85 mm, while the minimum allowable diameter was set to 1.65 mm. These limits were selected to ensure sufficient dimensional stability of the filament for subsequent application in the FDM 3D printing process.

3 Results

The analysis of the diameter of filament produced from recycled material represents an important factor in ensuring its dimensional stability, consistent quality, and reliability in the 3D printing process. Recycled polymer materials may exhibit a higher degree of variability in chemical composition and processing properties, which is often reflected in fluctuations of the extruded filament diameter. Variations in filament diameter can negatively affect the stability of material flow during the FFF printing process, lead to irregular material feeding, impair interlayer adhesion, and consequently reduce the geometrical accuracy and overall quality of the printed components. For these reasons, continuous monitoring and control of filament diameter are essential in order to minimize production deviations and ensure stable processing conditions during the manufacturing of filaments from recycled materials.

Furthermore, the control of filament dimensional accuracy represents an important aspect in improving the efficiency of material recycling and supporting environmentally sustainable manufacturing processes. Therefore, the objective of this part of the study was the analysis of the produced filament diameter.

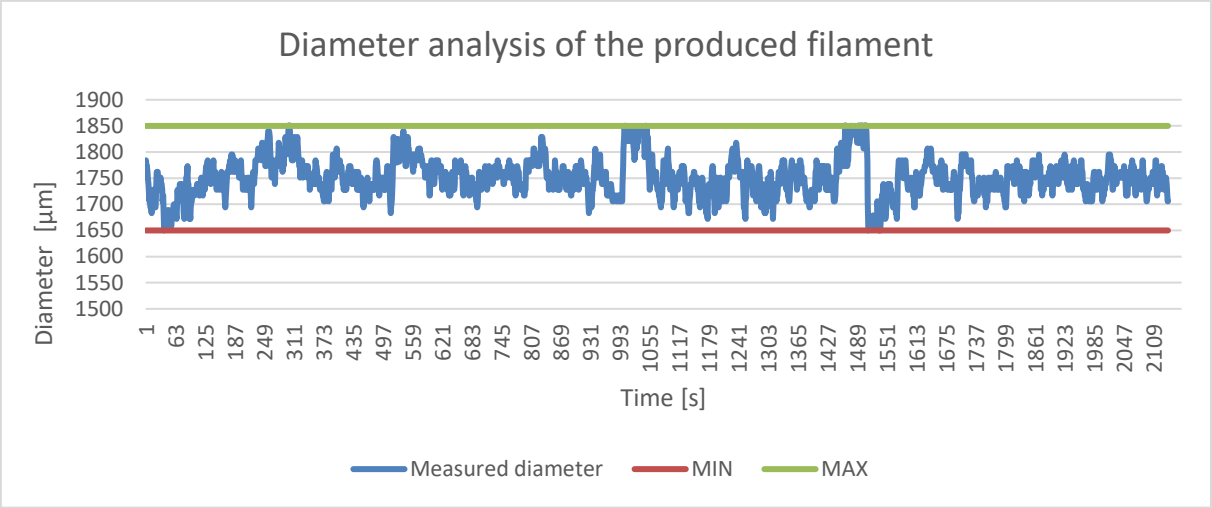


Figure 5 Diameter analysis of the produced filament

Figure 5 illustrates the temporal evolution of the measured filament diameter during the extrusion process of recycled PLA material. The horizontal axis (X-axis) represents the measurement time in seconds, while the vertical axis (Y-axis) shows the filament diameter values expressed in micrometers (µm). The blue curve represents the actual measured filament diameter values throughout the entire production process. The graph also includes upper and lower boundary limits defining the maximum and minimum allowable diameter tolerances of the filament. The measurement results indicate that the majority of the recorded values remained within the defined tolerance limits, demonstrating a relatively stable extrusion process and adequate quality control during filament production. In the initial stage of extrusion, a short-term increase in filament diameter toward the upper tolerance limit can be observed, which is likely associated with the stabilization of thermal and processing conditions after the start of extrusion. Following process stabilization, the diameter values fluctuated only slightly around the nominal value. During the measurement, local deviations in the form of short-term increases and decreases in filament diameter were also recorded, with some values approaching the upper or lower tolerance boundaries. These fluctuations may be attributed to changes in melted viscosity, inhomogeneity of the recycled material, or temporary variations in processing parameters during extrusion. In the second half of the recorded data, a sudden short-term drop or spike in the filament diameter was identified, after which the process stabilized again and continued within the defined tolerance limits. The results obtained confirm that the recycled filament production process was predominantly stable and well-controlled in terms of dimensional stability. Continuous monitoring of filament diameter represents an important quality control tool, as it enables real-time identification of process deviations, analysis of their causes, and optimization of extrusion parameters. Maintaining a stable filament diameter is essential for ensuring a reliable FFF 3D printing process, since even minor dimensional deviations may negatively affect printing accuracy, surface quality, and the mechanical properties of the final components. Overall, the analysis indicates that despite the natural fluctuations associated with the dynamics of the extrusion process, the control limits were appropriately defined, and the produced filament met the required quality criteria for subsequent processing.

Another method used for the analysis of the filament produced from recycled PLA material was the statistical evaluation of the measured diameter values using descriptive statistical methods. To assess the dimensional stability of the filament, the following basic statistical parameters were analyzed: arithmetic mean ($\bar{x}$), standard deviation (SD), median (MED), variance (s^2), skewness, kurtosis, minimum value (MIN), and maximum value (MAX). These statistical indicators enable a comprehensive assessment of the variability, distribution, and stability of the measured filament diameter values during the extrusion process. The calculated values of the individual parameters are presented in Table 3.

Table 3 Filament diameter analysis – descriptive statistics

Parameter	Value
Mean	1.747
Standard deviation	34.86
Median	1.746
Variance	1215.17
Skewness	-0.52
Kurtosis	0.17
Minimum value	1.65
Maximum value	1.851

The statistical results obtained indicate that, within the predefined filament diameter tolerance range (1.65 mm to 1.85 mm), the lower limit was not exceeded. A slight exceedance was recorded only for the maximum diameter value, which reached 1.851 mm. However, this exceedance represents a deviation of only 0.001 mm, which can be considered negligible in terms of FFF technology and without a significant effect on the quality of the 3D printing process.The average measured filament diameter during the production process reached a value of 1.747 mm, which corresponds, after rounding to the nominal diameter of 1.75 mm set prior to the extrusion process. This result confirms the appropriate adjustment of the processing parameters and the ability of the extrusion system to produce filaments with the required dimensional accuracy. Nevertheless, higher values of standard deviation (34.86) and variance (1215.17) were recorded during the extrusion process, indicating the presence of variability in the measured filament diameter values. This phenomenon may be associated with the inhomogeneity of the recycled feedstock material, particularly the varying granule sizes after the shredding process. Differences in granule size may influence the homogeneity of the melt and its rheological properties, especially viscosity, during the transition of the material from the solid to the viscous state, which may subsequently lead to minor fluctuations during the extrusion of the PLA material.

4 Conclusions

The aim of this study was to analyse the possibilities of recycling PLA material through a process involving mechanical shredding followed by filament extrusion for FFF 3D printing technology. The experimental results demonstrated that recycled PLA material can be successfully processed into filament with a diameter meeting the standard requirements for FFFprinting. The analysis of filament diameter and the results of descriptive statistics confirmed a relatively stable extrusion process, with most of the measured values remaining within the predefined tolerance limits. The observed deviations were minimal and were most likely related to the inhomogeneity of the input material and the varying granule sizes after the shredding process. The results of this study highlight the potential of recycling PLA waste for the re-production of filaments, thereby supporting material efficiency and environmentally sustainable approaches in the field of additive manufacturing. Future research could focus on the optimization of extrusion process parameters and the evaluation of the mechanical properties of recycled filament after multiple recycling cycles.

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In vitro differentiation of chorionic mesenchymal stem cells for applications in biomedical engineering

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Keywords: mesenchymal stem cells, differentiation, regenerative medicine, tissue engineering, in vitro.
Abstract: Mesenchymal stem cells (MSCs) are multipotent stromal cells with significant regenerative potential. This study evaluates the differentiation capacity of chorionic mesenchymal stem cells (CMSCs) into adipogenic, osteogenic, and chondrogenic lineages under in vitro conditions. Experimental results confirmed successful lineage specification using histological staining methods. Adipogenic differentiation was characterized by lipid accumulation, osteogenic differentiation by mineralized matrix formation, and chondrogenic differentiation by extracellular matrix production. The findings highlight the applicability of CMSCs in regenerative medicine and tissue engineering, particularly in scaffold-based systems and advanced therapeutic strategies. These findings contribute to the growing body of knowledge on MSC-based applications in biomedical engineering.

1 Introduction

Mesenchymal stem cells (MSCs) are multipotent stromal cells characterized by their ability to self-renew and differentiate into multiple cell lineages, including adipocytes, osteocytes, and chondrocytes [1]. Due to these properties, MSCs have become a key focus in regenerative medicine and tissue engineering, where they are utilized for the repair and regeneration of damaged tissues [2]. MSCs can be isolated from various sources, such as bone marrow, adipose tissue, and perinatal tissues. Among these, chorionic mesenchymal stem cells (CMSCs) represent a promising alternative due to their accessibility, high proliferative capacity, and reduced invasiveness of collection procedures [3]. In addition, perinatal tissues raise fewer ethical concerns compared to embryonic sources, further supporting their use in biomedical applications. Recent studies have emphasized the critical role of microenvironmental factors in regulating stem cell behaviour. Parameters such as biochemical signaling, extracellular matrix composition, and mechanical properties (e.g., substrate stiffness) significantly influence differentiation pathways and lineage specification [4,5]. These findings are particularly relevant for biomedical engineering, where scaffold design and biomaterial properties are created to guide cell fate and enhance tissue regeneration. Despite extensive research on MSCs, the differentiation potential of CMSCs under standardized in vitro conditions remains an important area of investigation, particularly in the context of their applicability in biomedical engineering systems. Understanding their behavior after initial passages is essential for ensuring reproducibility and reliability in experimental and clinical applications. Therefore, the aim of this study is to evaluate the in vitro differentiation potential of chorionic mesenchymal stem cells into adipogenic, osteogenic, and chondrogenic lineages and to assess their suitability for applications in biomedical engineering, particularly in tissue engineering and regenerative medicine.

2 Materials and Methods

Chorionic mesenchymal stem cells (CMSCs) were isolated from chorionic tissue and cultured under standard in vitro conditions. Cells were maintained in a humidified incubator at 37 °C with 5% CO_2 in a precisely defined complete culture medium consisting of a mixture of DMEM and α-MEM *(Thermo Fisher Scientific, Gibco, California, USA*) in a ratio of 1:1, supplemented with 10% fetal bovine (*Thermo Fisher Scientific, Gibco, California, USA*) serum and 1% antibiotic-antimycotic solution (*Thermo Fisher Scientific, Gibco, California, USA*). After reaching approximately 80–90% confluence, cells were passaged and subsequently used for differentiation experiments. Adipogenic differentiation was induced using a culture medium supplemented with insulin, dexamethasone, and other adipogenic factors. The differentiation process was monitored over a period of 14–21 days. The presence of intracellular lipid droplets was

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evaluated using Oil Red O staining, which specifically binds to neutral lipids. Osteogenic differentiation was performed using osteoinductive medium containing β-glycerophosphate, ascorbic acid, and dexamethasone. Mineralization of the extracellular matrix was assessed using Von Kossa staining, which detects calcium phosphate deposits. Chondrogenic differentiation was induced using a specialized medium promoting the synthesis of cartilage-specific extracellular matrix components. Glycosaminoglycan production was confirmed using Alcian blue staining. All experiments were conducted under sterile laboratory conditions. Morphological changes were monitored using light microscopy, and differentiation was evaluated qualitatively based on staining intensity and cell morphology, in accordance with established protocols [6,7], as well as studies focused on MSC applications in biomedical engineering [8-10].

3 Results

During in vitro cultivation, CMSCs exhibited typical spindle-shaped fibroblast-like morphology (Figure 1). Cells adhered to the culture surface within 24 hours and formed a homogeneous monolayer after approximately 7–10 days of cultivation.

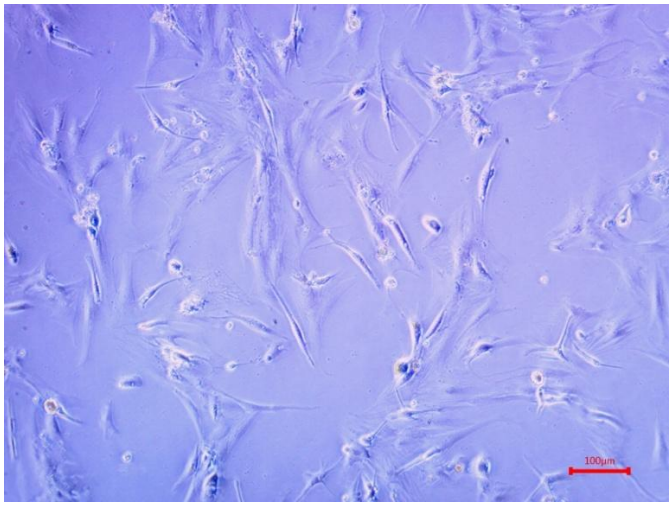


Figure 1 Microscopic image of CMSCs displaying typical spindle-shaped fibroblast-like morphology and adherent growth pattern. Cells are well distributed across the culture surface with elongated cytoplasmic extensions, indicating healthy morphology and active proliferation. Scale bar: 100 µm.

Following adipogenic induction (Figure 2), visible intracellular lipid droplets were observed after approximately 10–14 days. The intensity of Oil Red O staining increased over time, indicating progressive lipid accumulation and successful adipogenic differentiation. The proportion of positively stained cells increased throughout the cultivation period, suggesting stable differentiation efficiency.

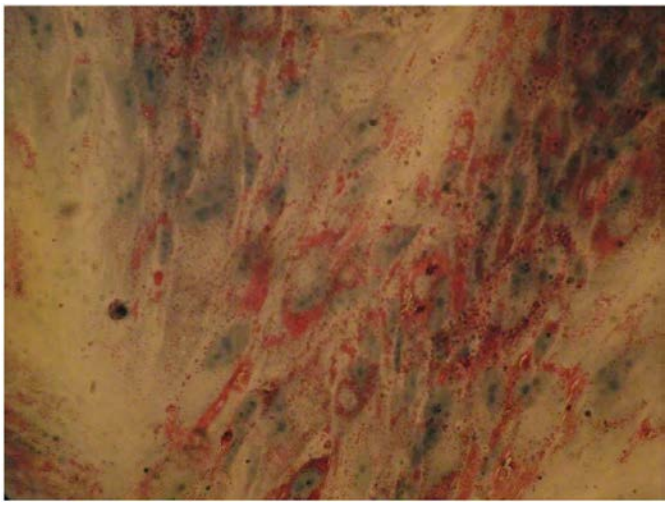


Figure 2 Microscopic image of adipogenic differentiation of CMSCs showing intracellular accumulation of lipid droplets stained red, indicating successful adipogenic lineage differentiation. Cells exhibit elongated morphology with scattered lipid-rich regions characteristic of adipocyte formation.

Osteogenic differentiation resulted in the formation of mineralized nodules, which became evident after approximately 14–21 days. *Von Kossa* staining confirmed the presence of calcium deposits, indicating extracellular matrix mineralization and osteoblastic lineage commitment.

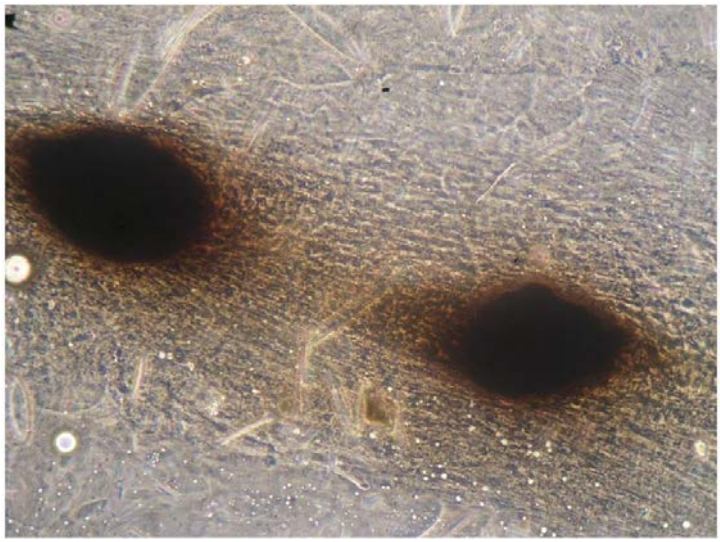


Figure 3 Microscopic image of osteogenic differentiation of CMSCs demonstrating formation of mineralized extracellular matrix deposits visible as dark-stained nodular areas. Surrounding cells exhibit elongated morphology and dense growth pattern, confirming successful osteogenic lineage differentiation and matrix mineralization.

Chondrogenic differentiation (Figure 4) was characterized by the production of glycosaminoglycan-rich extracellular matrix. Alcian blue staining revealed an increasing intensity of extracellular matrix deposition over time. Cells gradually adopted a rounded morphology typical of chondrocytes.

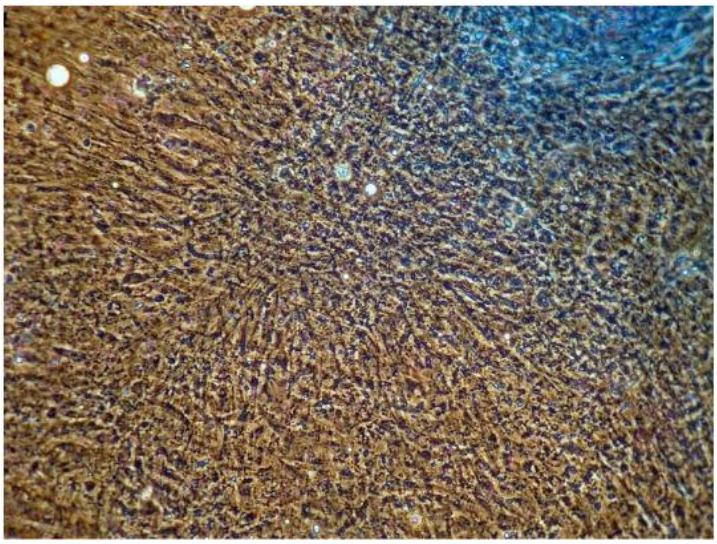


Figure 4 Chondrogenic differentiation of CMSCs stained with Alcian blue. Figure shows a highly confluent cell culture exhibiting dense cellular aggregation and the formation of characteristic chondrogenic nodules. This tight packing and opaque appearance indicate active extracellular matrix (ECM) production and successful transition toward a chondrocyte-like phenotype.

Overall, CMSCs demonstrated stable and reproducible differentiation into all three lineages after the first passage. These findings are consistent with previously reported characteristics of mesenchymal stem cells derived from perinatal tissues [3,8]. No significant morphological abnormalities were observed during differentiation.

4 Discussion

The results of this study confirm that chorionic mesenchymal stem cells retain their multipotent differentiation capacity under standard in vitro conditions. The observed morphological changes and staining patterns correspond with well-established markers of adipogenic, osteogenic, and chondrogenic differentiation [1,3]. The progressive increase in

staining intensity during differentiation suggests a time-dependent maturation process, which is consistent with findings reported in previous studies [4]. These results indicate that CMSCs respond effectively to biochemical stimuli and maintain stable differentiation potential after initial passages. From the perspective of biomedical engineering, these findings are particularly significant. The ability of CMSCs to differentiate into multiple lineages makes them suitable candidates for scaffold-based tissue engineering applications. Previous studies have demonstrated that the combination of MSCs with biomaterials and three-dimensional scaffolds enhances differentiation efficiency and improves tissue regeneration outcomes [5,9].

In comparison with bone marrow-derived MSCs, CMSCs offer several advantages, including less invasive harvesting procedures and higher proliferative capacity. Similar observations have been reported in studies by Trebuňová et al. and Bačenková et al., which highlight the potential of perinatal stem cells in regenerative medicine and biomedical applications [8,9]. Furthermore, Čajková et al. emphasized the importance of microenvironmental conditions and biomaterial interactions in directing stem cell behaviour [10]. Despite these advantages, certain limitations must be considered. Variability between donors and sensitivity to culture conditions may influence experimental outcomes. In addition, in vitro models do not fully replicate the complexity of in vivo environments, which may affect the translation of results into clinical practice.

Future research should focus on optimizing culture conditions, integrating advanced biomaterials, and developing standardized protocols to improve reproducibility and facilitate clinical application of CMSCs in biomedical engineering. These findings confirm the robustness of CMSCs as a reliable cell source for biomedical engineering applications [11,12].

5 Conclusions

Chorionic mesenchymal stem cells demonstrate stable and reproducible differentiation into adipogenic, osteogenic, and chondrogenic lineages under in vitro conditions. Their biological properties, including accessibility, high proliferation capacity, and multipotency, make them promising candidates for applications in biomedical engineering and regenerative medicine. The results of this study support the use of CMSCs in tissue engineering systems, particularly in combination with biomaterials and scaffold-based approaches. Further research is required to optimize differentiation protocols and enhance clinical translation.

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Development of silicone anatomical facial models intended for surgical suturing training

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Keywords: anatomical training model, surgical suturing, silicone casting, 3D printing, medical simulation.
Abstract: Simulation-based training plays an important role in surgical education by providing a safe environment for developing practical skills. However, commercially available suturing simulators are often expensive and offer limited possibilities for anatomical customization. The aim of this study was to develop a low-cost anatomical eyebrow model for surgical suturing training using three-dimensional (3D) scanning, additive manufacturing, and silicone casting technologies. A 3D scan of the facial region was acquired and processed to create a digital model of the eyebrow area. A simulated laceration was incorporated into the model using computer-aided design (CAD) tools. A two-part mould was designed and manufactured using fused deposition modelling (FDM) 3D printing. The final training model was produced by casting a two-component silicone elastomer into the printed mould. Manufacturing feasibility, production costs, and functional usability were evaluated. The proposed workflow successfully enabled the fabrication of an anatomically shaped silicone eyebrow model suitable for practising basic suturing techniques, including needle handling, wound-edge approximation, and knot tying. The prototype accurately reproduced the intended anatomical geometry and wound morphology. The total material cost of the first prototype, including mould fabrication and silicone casting, was approximately €4.89, while subsequent models can be produced at substantially lower cost due to mould reusability. Functional testing confirmed the suitability of the model for basic surgical skills training. The results demonstrate that the combination of 3D scanning, CAD modelling, additive manufacturing, and silicone casting provides a feasible and cost-effective approach for developing customized anatomical training models for surgical education.

1 Introduction

Simulation-based medical education has become an integral component of modern surgical training, providing a safe and controlled environment for the development of technical skills before their application in clinical practice [1-4]. In surgical education, simulation enables repetitive practice of suturing techniques, needle handling, knot tying, and tissue manipulation without exposing patients to unnecessary risk. Numerous studies have demonstrated that simulation-based training improves technical proficiency, confidence, and overall clinical performance while contributing to patient safety [1,2,4].

A wide range of training models has been developed for surgical suturing education. These models can be broadly categorized as biological, improvised, commercial synthetic, and additive-manufactured models. Biological models, including animal tissues and cadaveric specimens, provide the highest degree of anatomical and tactile realism due to their natural tissue architecture and mechanical properties [5-9]. However, their routine use is limited by ethical concerns, hygiene requirements, storage conditions, restricted availability, and higher operational costs [7,9].

Improvised training models, such as fruit, foam, or textile-based substitutes, represent a low-cost alternative for acquiring basic suturing skills. Although suitable for developing fundamental hand–eye coordination and instrument handling, these models fail to reproduce the layered structure and biomechanical behaviour of human tissue, limiting their value for advanced surgical training [5,6,10]. Synthetic commercial simulators offer improved standardization and repeatability, but their cost often restricts widespread adoption, particularly when anatomically detailed or multilayered models are required [6,11].

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Recent advances in additive manufacturing have created new opportunities for the development of customized surgical training models. Additive manufacturing enables the fabrication of anatomically accurate structures with high reproducibility and relatively low production costs [12-15]. In particular, the combination of 3D-printed moulds and silicone casting has emerged as a promising approach for producing realistic soft-tissue simulators. Silicone-based materials are widely used because of their biocompatibility, durability, and ability to mimic the viscoelastic properties of human skin [16,17]. Furthermore, additive manufacturing allows the production of patient-specific or anatomically targeted models, thereby enhancing the educational relevance of simulation-based training [12,14].

Despite significant progress in surgical simulation, no currently available model simultaneously provides high anatomical fidelity, realistic mechanical behaviour, affordability, durability, and ease of customization. Consequently, there remains a need for training models that effectively combine these characteristics while remaining accessible for routine educational use. Therefore, the present study focuses on the design and fabrication of silicone anatomical facial models for surgical suturing training using a combination of CAD (Computer Aided Design) modelling, additive manufacturing, and silicone casting technologies. The proposed approach aims to provide a cost-effective and anatomically realistic training platform suitable for the development of practical suturing skills in facial surgery.

2 Methodology

The design process began with the definition of functional and ergonomic requirements for a silicone anatomical trainer intended for practising suturing techniques in selected facial regions. The model was required to provide realistic handling during needle penetration, suture tightening, knot tying, and wound-edge approximation. Attention was given to material elasticity, tensile behaviour, resistance to tearing, haptic feedback, and compatibility with standard surgical instruments. These requirements were based on previously reported mechanical characteristics of artificial skin and soft-tissue simulators, especially Young's modulus, tensile strength, viscoelastic behaviour, and puncture-related response [16,18].

From an ergonomic perspective, the model had to be compact, stable during manipulation, easy to handle, and suitable for repeated training. The geometry was designed to reproduce clinically relevant facial regions while preserving sufficient space for the manipulation of forceps, needle holders, and sutures. Stability during training was considered essential, as uncontrolled movement of the model can negatively affect the realism and repeatability of the exercise [15,19].

The eyebrow region was selected for the development of the anatomical suturing model due to its suitability for basic surgical skills training. This anatomical area provides sufficient geometric complexity to simulate realistic clinical conditions while remaining appropriate for practising fundamental techniques such as needle handling, wound-edge approximation, knot tying, and suture placement. Furthermore, the eyebrow region is a common site of facial lacerations encountered in clinical practice, making it relevant for educational applications. Consequently, all subsequent stages of digital modelling, mould design, fabrication, and functional evaluation were focused exclusively on the development of an anatomical eyebrow model.

2.1 Digital modelling of a simulated defect

A 3D scan of a human head was used as the basis for the development of the anatomical eyebrow model. The scan was acquired under stable indoor lighting conditions using a handheld structured-light 3D scanner Artec Eva (Artec 3D, Luxembourg, Luxembourg), with the scanning frequency of 16 fps (framer per second). The raw scan data were processed to remove environmental artefacts and irrelevant geometry in Artec Studio 13 (Artec 3D, Luxembourg, Luxembourg) software. The cleaned polygonal mesh was exported in STL format and used for subsequent computer-aided design processing.

The STL model was imported into Autodesk Meshmixer (Autodesk, Inc., San Francisco, CA, USA) CAD software, where the eyebrow region was isolated from the complete facial scan (Figure 1 – a). Mesh complexity was reduced to improve computational efficiency while preserving clinically relevant anatomical features. Surface irregularities resulting from the scanning process were corrected using smoothing and sculpting tools to obtain a clean and anatomically representative model suitable for further modification. The simulated laceration was subsequently incorporated into the eyebrow model. The defect was created using an auxiliary geometric body that was subtracted from the anatomical surface through a Boolean operation. The resulting wound geometry was further refined using sculpting tools to generate realistic wound edges and tissue contours. The final defect (Figure 1 – b) was designed to facilitate the practice of fundamental suturing techniques, including interrupted sutures, wound-edge approximation, and knot tying. The position, dimensions, and geometry of the simulated wound can be modified according to specific training requirements, enabling the creation of customized training scenarios.

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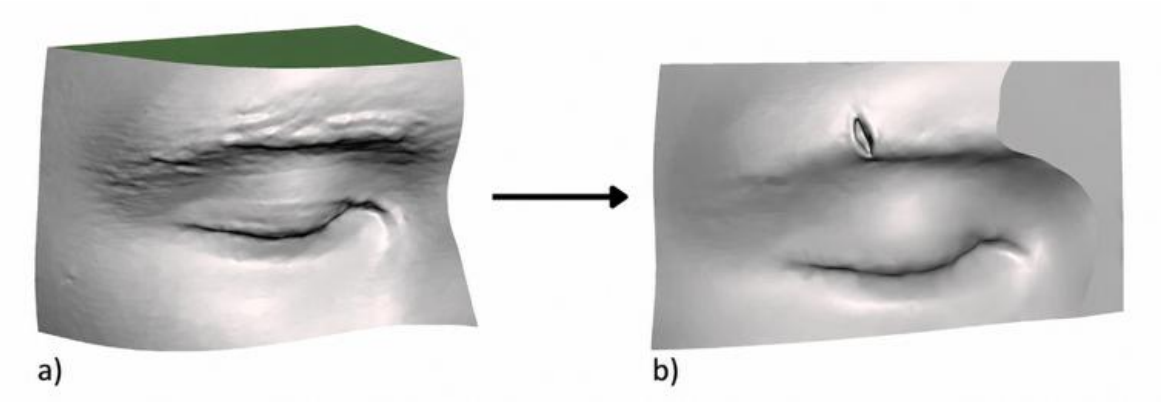


Figure 1 Digital model of the eyebrow before (a) and after (b) defect creation

2.2 Design of moulds for silicone casting

The mould for the anatomical eyebrow model (Figure 2) was designed in Autodesk Meshmixer. The mould geometry was created by generating a negative cavity through the subtraction of the anatomical model from a solid block. A two-part mould configuration was selected to allow straightforward fabrication, assembly, and demoulding of the final silicone cast. The mould incorporated alignment pins and corresponding sockets to ensure accurate positioning of both mould halves during assembly. In addition, a main inlet channel and multiple ventilation channels were integrated into the design to facilitate controlled silicone injection and efficient air evacuation during the casting process. The position of the parting plane was carefully selected to minimize undercuts, simplify demoulding, and reduce the risk of damaging the silicone model during removal from the mould. These design features were incorporated to improve manufacturing reproducibility and ensure consistent production of anatomically accurate silicone training models.

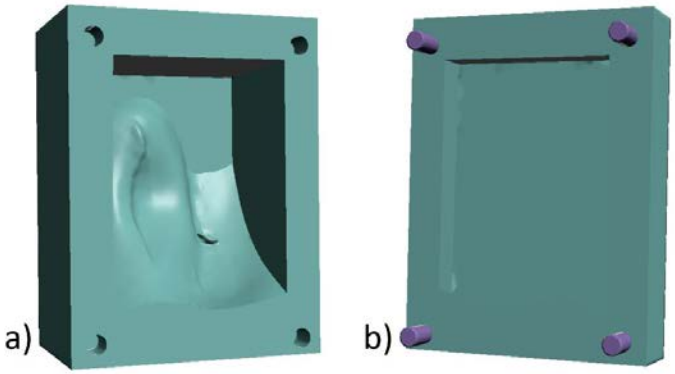


Figure 2 Digital mould design for the anatomical eyebrow model (a – negative cavity, b – mould cover with alignment pins)

2.3 Additive manufacturing of moulds

The mould was manufactured using the iFactory One Pro (iFactory3D GmbH, Dusseldorf, Germany) FDM (Fused Deposition Modelling) printer. The digital mould file was prepared in slicing software ideaMaker (iFactory3D GmbH, Dusseldorf, Germany) with a layer height of 0.2 mm, providing a suitable balance between surface quality and manufacturing time (Figure 3). The mould was printed from polyethylene terephthalate glycol (PETG), a material selected for its toughness, dimensional stability, and resistance to mechanical loading during mould assembly and silicone casting. To reduce material consumption while maintaining sufficient structural rigidity, a low infill density was applied. The mould was oriented on the build platform to avoid the use of support structures, thereby simplifying post-processing and reducing printing time. Following slicing, the generated G-code was transferred to the FDM printer for fabrication of the mould components.

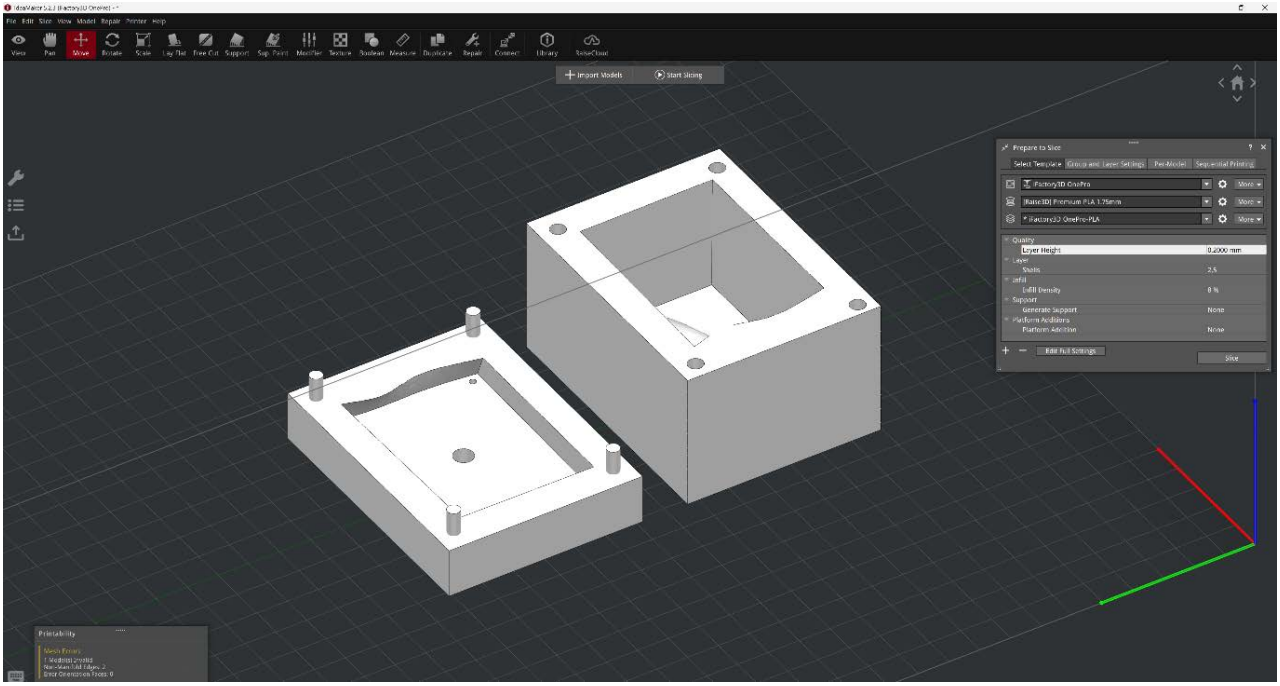


Figure 3 Preparation of the mould for 3D printing

2.4 Silicone casting and post-processing

A two-component casting silicone (EPOXY s.r.o, Vysoká pri Morave, Slovakia) was used for the fabrication of the anatomical eyebrow model. Prior to casting, the internal surfaces of the mould were coated with a thin layer of release agent to facilitate demoulding and prevent adhesion between the silicone and the mould walls. The mould components were subsequently assembled and mechanically secured using clamps to ensure accurate alignment and maintain sufficient pressure during casting. The silicone components were weighed according to the manufacturer's recommended mixing ratio of 1:1 and thoroughly mixed until a homogeneous mixture was obtained. The silicone was then injected into the mould through the inlet channel using a syringe (Figure 4 – a). Injection continued until material emerged from the ventilation channels, indicating complete filling of the mould cavity and displacement of trapped air (Figure 4 – b). The mould remained closed throughout the curing process to maintain dimensional accuracy and prevent deformation of the final model (Figure 4 – c). After complete curing, the mould was disassembled and the silicone eyebrow model was carefully removed. Residual material originating from the inlet channel, ventilation channels, and parting line was removed by mechanical trimming. Finally, the model was cleaned to eliminate any remaining release-agent residues, and a thin layer of fine talc was applied to the surface to reduce tackiness and provide a more realistic matte texture resembling human skin.

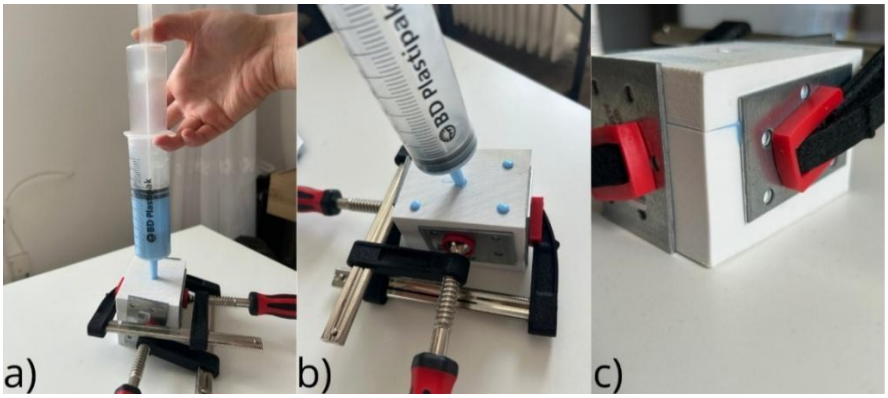


Figure 4 Silicone casting process, including mould fixation, injection, and demoulding

After curing, the mould was disassembled and the silicone model was removed. Excess material from the inlet, ventilation channels, and parting line was mechanically trimmed. The model was cleaned to remove separation residues, and the surface was treated with fine talc to reduce tackiness and create a more skin-like matte appearance.

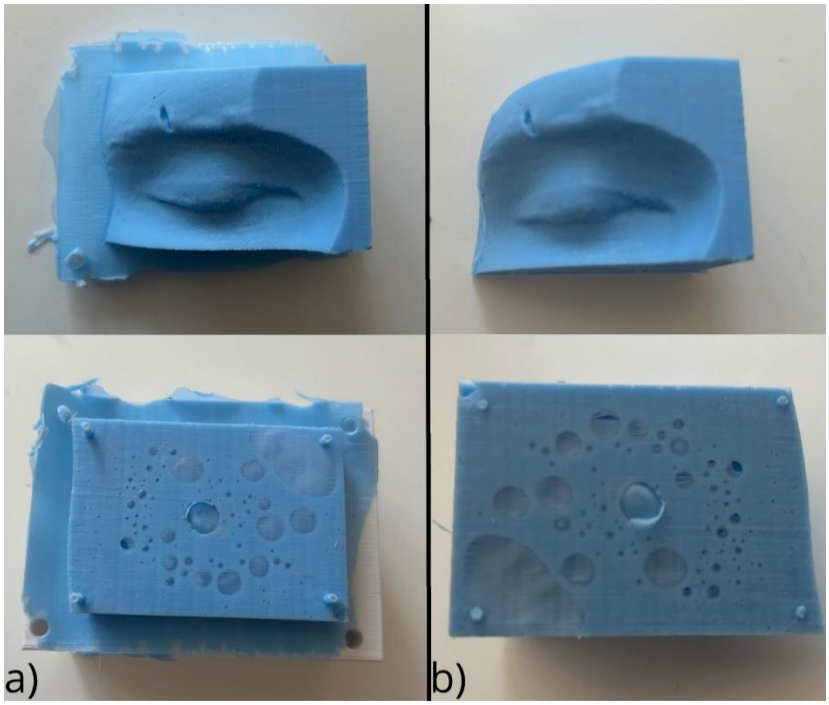


Figure 5 Silicone anatomical model before (a) and after (b) postprocessing

2.5 Functional testing

The eyebrow prototype was evaluated by practical suturing using standard surgical instruments (Figure 6). Testing was performed by a fourth-year medical student familiar with basic surgical techniques. The evaluation focused on haptic response, resistance to needle penetration, wound-edge approximation, material behaviour during knot tying, stability of the model, and overall usability. A structured evaluation form was used. Quantitative parameters were rated on a five-point scale, where 1 represented an unsatisfactory result and 5 represented an excellent result. Qualitative feedback was also collected to identify specific strengths and limitations of the prototype.

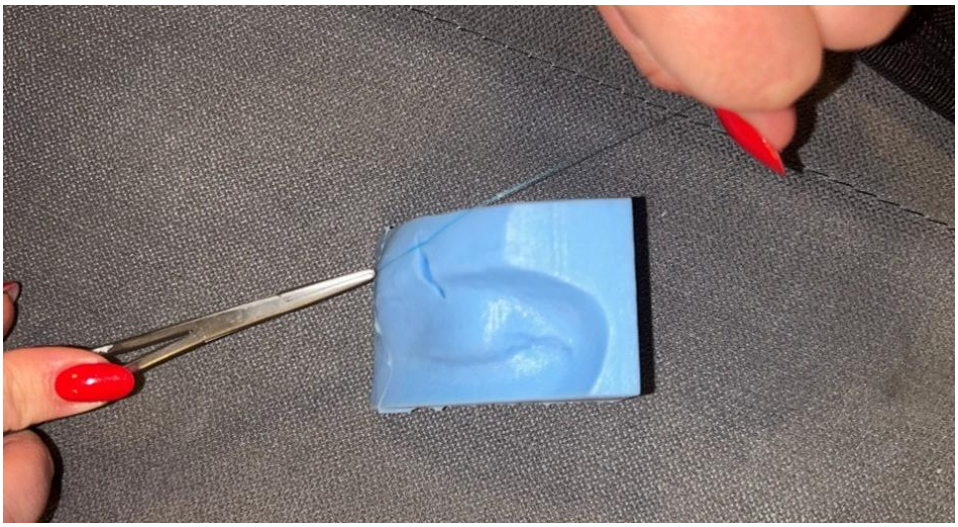


Figure 6 Functional suturing test performed on the eyebrow prototype

2.6 Economic and environmental assessment

The economic assessment included material consumption for the printed moulds and silicone casts. The moulds were considered reusable; therefore, the main variable cost for repeated production was the silicone volume required for each cast. The environmental assessment focused on material waste, reusability of moulds, elimination of biological waste, and the limitations associated with non-biodegradable silicone materials.

3 Results

3.1 Functional suturing test

Functional testing (Figure 7) demonstrated that the prototype could be used for basic suturing practice. The model remained stable during manipulation and allowed the use of standard surgical instruments. The anatomical shape and wound depth were positively evaluated, particularly in comparison with flat suturing pads.

However, the material properties of the initial silicone were rated as unsatisfactory in all quantitative categories. Haptic response, needle penetration resistance, wound-edge approximation, and resistance to tearing during knot tying were all rated 1 out of 5. The main limitation was the excessive stiffness of the silicone material, which did not adequately reproduce the behaviour of human soft tissue. Similar limitations have been reported in synthetic simulators when the mechanical properties of the material do not correspond sufficiently to biological tissue.

Despite this limitation, the tester considered the anatomical geometry and wound configuration useful for basic training. The feedback indicated that material optimization is necessary before broader educational use.



Figure 7 Final sutured eyebrow prototype

3.2 Cost analysis and enviromental assessment

The material cost (Table 1) of the printed mould was low, amounting to approximately €1.95 for the anatomical eyebrow model. As the mould is designed for repeated use, this cost represents a one-time investment that can be distributed across multiple castings. The silicone consumption (Table 1) for a single eyebrow model was 113 g, corresponding to a material cost of approximately €2.94 per cast. Consequently, the total material cost of manufacturing the eyebrow prototype, including both the 3D-printed mould and the silicone cast, was approximately €4.89. For subsequent productions, the manufacturing cost would be limited primarily to the silicone material, resulting in a significantly lower unit cost per model.

Table 1 Material and silicone consumption and model cost

Model	Material amount [g]	Cost [euro]
Printed mould (PETG)	95.8	1.95
Silicone cast	113.00	2.94

The proposed workflow eliminates the use of animal or cadaveric tissues and therefore avoids the generation of biological waste. The reusable mould design further reduces material consumption during repeated production. The main environmental limitation is the use of silicone, which is chemically stable but not biodegradable. Nevertheless, the low material consumption, reusability of moulds, and local production process reduce waste compared with disposable or biologically derived training materials.

4 Discussion

The present study describes the development of silicone anatomical facial models for suturing training using 3D scanning, CAD modelling, additive manufacturing, and silicone casting. The proposed workflow demonstrates that anatomically shaped training models can be produced at low material cost while preserving the possibility of customization. This is consistent with previous studies showing that 3D printing can improve access to surgical training models and support task-specific simulation in medical education [12-15].

A key strength of the proposed approach is the integration of real anatomical geometry into the training model. Unlike flat suturing pads, anatomically shaped models provide spatial orientation and clinically relevant geometry, which may improve the realism of the training task. The eyebrow region was selected as the target anatomical area because it provides

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an appropriate environment for practising fundamental surgical suturing skills, including needle handling, wound-edge approximation, and knot tying. In addition, the eyebrow is a clinically relevant facial region frequently affected by lacerations requiring precise wound closure. The development of an anatomically shaped eyebrow model demonstrates the potential of additive manufacturing technologies to create customized training tools tailored to specific educational objectives in surgical training [12,14].

The results demonstrated the technical feasibility of the proposed digital and manufacturing workflow. The eyebrow mould was successfully fabricated using additive manufacturing and subsequently used for silicone casting. The resulting prototype accurately reproduced the intended anatomical geometry of the eyebrow region as well as the designed wound defect intended for suturing practice. The casting process yielded a functional silicone model suitable for basic surgical suturing exercises. The final prototype exhibited satisfactory anatomical fidelity and enabled the practice of wound-edge approximation, needle handling, and knot tying under anatomically relevant conditions. Minor manufacturing imperfections, including localized silicone leakage and air bubbles, were observed primarily on the posterior side of the model. However, these defects did not affect the anatomical surface or the functional area intended for training and therefore had no significant impact on the practical usability of the prototype.

The functional test confirmed that the prototype can be used for basic suturing practice but also revealed important material limitations. The initial silicone was too stiff and did not provide sufficiently realistic haptic feedback, needle penetration resistance, or wound-edge approximation. This finding is important because the educational value of a suturing simulator depends not only on anatomical geometry, but also on the mechanical similarity of the material to human tissue [16,18]. Previous studies have shown that artificial skin models should reproduce key biomechanical properties, including tensile behaviour, viscoelastic response, and resistance to tearing [16]. Therefore, further material optimization is necessary.

Although the material properties were not optimal, the anatomical design of the wound was positively evaluated. The tester reported that the wound depth and shape were more realistic than those of standard flat suturing pads. This suggests that geometric realism and material realism should be considered as complementary design requirements. In the present prototype, the geometric component was successful, whereas the material component requires further development. This finding supports the need for an iterative design strategy combining digital geometry optimization with experimental mechanical testing.

A major advantage of the proposed model is its low production cost. The material cost of a single silicone cast was substantially lower than the cost typically associated with commercial anatomically shaped trainers. In addition, the moulds are reusable, which further reduces the cost of repeated production. This makes the proposed workflow potentially suitable for educational environments with limited resources. Low-cost models may support repeated individual practice, which is considered important for the development of surgical skills [10,13].

The model also has environmental and practical advantages. It eliminates the need for animal or cadaveric tissue and therefore avoids ethical concerns, storage requirements, and biological waste. In contrast to biological models, silicone trainers are easier to store, handle, and reproduce. However, silicone is not biodegradable, and its long-term environmental impact should be considered. Reusable moulds and controlled material consumption partly reduce this limitation.

This study has several limitations. First, the functional evaluation was performed using only a single anatomical eyebrow model, which limits the ability to assess the applicability of the proposed methodology to other facial regions. Second, functional testing was conducted by a single medical student, and therefore the findings cannot be generalized to a broader population of users with different levels of surgical experience. Third, the mechanical properties of the fabricated silicone model were not experimentally characterized. Consequently, parameters such as tensile strength, puncture resistance, tear resistance, and elasticity were not quantitatively compared with reported values for human skin or synthetic training materials [16,18]. Finally, the model was not evaluated by experienced surgeons, and therefore its educational value, content validity, and clinical realism remain to be verified through expert assessment.

Future work should focus on the selection and testing of softer silicone elastomers with lower Shore A hardness and improved tear resistance. Multilayered casting could also be explored to better reproduce the structure of skin and subcutaneous tissue. In addition, larger-scale validation involving medical students and surgeons would allow assessment of construct validity and training effectiveness.

Overall, the proposed approach provides a feasible and low-cost method for producing customized silicone anatomical models for facial suturing training. Although the current prototype requires material and mould optimization, the results demonstrate the potential of combining 3D scanning, CAD modelling, additive manufacturing, and silicone casting for the development of accessible and anatomically relevant surgical training tools.

5 Conclusions

This study presented a workflow for the development of silicone anatomical facial models intended for surgical suturing training. The proposed approach combined 3D facial scanning, CAD modelling, additive manufacturing of casting moulds, and silicone casting to create anatomically representative training models of a selected facial region. The developed methodology enabled the creation of customized models containing clinically relevant defects suitable for

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practising wound closure techniques. The fabricated prototype demonstrated the feasibility of producing anatomically shaped suturing trainers using readily available manufacturing technologies and low-cost materials. In addition, the use of reusable 3D-printed moulds allows efficient and repeatable production of training models while maintaining a high degree of geometric customization. The presented approach provides an accessible alternative to commercially available training simulators and demonstrates the potential of combining digital anatomical data with additive manufacturing technologies for medical education. The results support the use of personalized silicone models as a promising platform for the development of practical surgical skills in a safe and controlled training environment.

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