# SYNERGY OF DIVERSITY
## DATA, MODELING AND DECISIONS

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# STRESS IN BUSINESS AND FEAR OF FAILURE VERSUS ENTREPRENEURS' PERSONAL AND FINANCIAL RESOURCES

KATARZYNA BIEGAŃSKA

ABSTRACT. The present research aims to elucidate the relationships between entrepreneurial stress, fear of failure, and both psychological and financial resources. The study sample comprised entrepreneurs who owned either newly established businesses (enterprises registered for up to 42 months) or more established ventures (those registered for more than 42 months). In total, 349 participants were surveyed, of whom 155 were classified as new entrepreneurs and 194 as mature entrepreneurs. The following tools were used: The SES Self-Esteem Scale developed M. Rosenberg, Generalised Self-Efficacy Scale (GSES) developed Schwarz and Jerusalem; Perceived Stress Scale PSS-10 developed by Cohen, Kamarcka, Mermeinstein, own questionnaire for measuring fear of failure, financial and sociodemographic variables. The findings of this study support the division of the entrepreneurial sample into two cohorts based on business experience (up to 42 months and over 42 months). Psychological resources—specifically, hope for success (with particular emphasis on the volitional component), self-esteem, and perceived self-efficacy — demonstrate significant associations with experienced stress and fear of failure. The results indicate that these psychological resources function as determinants of psychological stress.

## 1. Introduction

Research into entrepreneurship, its determinants, and economic efficiency is primarily undertaken due to the substantial economic advantages associated with entrepreneurial activity. Economic growth and innovation are driven by the predispositions, enthusiasm, and perseverance of individuals who pursue this career path despite considerable burdens and business risks. Nevertheless, a significant proportion of businesses discontinue operations within their initial years (Baron, 2013; Zaleśkiewicz, 2011). While financial failure is most frequently cited as the primary cause, the psychological burdens encountered by entrepreneurs also play a pivotal role (Ucbasaran et al., 2013). The psychological costs associated with entrepreneurial work are shaped by both the demands of the business environment and the subjective predispositions of entrepreneurs themselves. Psychological resources—such as hope for success, self-efficacy, and self-esteem (as components of psychological capital)—constitute significant assets for entrepreneurs, enhancing their resilience to stress. Similarly, financial and material resources (for example, income level, income growth, income security, and satisfaction with income) may fulfil a comparable function. Financial success in business is indispensable for the survival of the entrepreneur and the security of their own and their family's well-being, a factor that is inextricably linked to stress and the fear of failure.

The presented article contains a theoretical analysis of the main variables as well as the results of empirical research. The aim of the study is to verify the relationships and dependencies between stress in business and fear of failure and personal resources (psychological capital) and financial resources.

## 2. Stress in Business

The role of the entrepreneur is widely recognised as one of the most mentally demanding career paths. Business owners encounter significant stress both during the start-up phase and throughout the ongoing

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management of their enterprises. This stress primarily arises from financial and organisational responsibilities, the risk of failure—which may result in personal financial deterioration—and the necessity to operate under time pressure amid uncertainty and competition (Xie et al., 2008). Entrepreneurs also report higher levels of work-family conflict and lower family satisfaction compared to salaried employees (Cardon & Patel, 2015; Patzelt & Shepherd, 2011; Markman et al., 2005).

Owners of small and medium-sized enterprises typically fulfil managerial functions, including hiring, motivating, supervising, and bearing responsibility for their employees. They frequently work under time constraints and must make critical decisions without complete information regarding potential consequences. The diversity of tasks, coupled with the dynamic market environment, necessitates continuous learning and maximisation of cognitive effort. Entrepreneurs tend to identify strongly with their professional role, often working harder and longer than full-time employees (Dolinsky & Caputo, 2003; Prottas & Thompson, 2006). Many perceive themselves as irreplaceable, with a substantial proportion becoming workaholics, working in excess of 60 hours per week, including nights and weekends (Bradley & Roberts, 2004).

Grant and Ferris (2012) identified approximately thirty sources of stress in the entrepreneurial context, categorising them into six domains: financial stress (competition, financing, operations, cash flow), interpersonal stress (lack of support, loneliness, client and employee issues, supervision, recruitment), internal stress (e.g., disappointment following failure, need for recognition), task type, unpredictability/risk (ambiguity, uncertainty), and work-life balance (difficulty resting, lack of genuine free time, extended working hours). Schonfeld and Mazzola (2015), in a qualitative study of 54 sole traders, found that the most prevalent stressors were income uncertainty, threats to reputation, and dishonesty within the business environment. Signs of exhaustion, anxiety, frustration, anger, sadness, and depression were observed among entrepreneurs.

It is noteworthy that moderate work-related stress may be beneficial, mobilising personal resources and resulting in positive arousal (eustress). However, excessive or prolonged stress (distress) leads to tension and anxiety, with adverse physical, psychological, and behavioural consequences that negatively impact health, well-being, and work performance. Research by Kariv (2008) demonstrated that eustress is positively associated with sales turnover, whereas distress has the opposite effect. Some studies suggest that entrepreneurs experience less stress than other professional groups (Baron et al., 2016; Cohen & Janicki-Deverts, 2012; Tarnawai et al., 2014). Baron, Franklin, and Hmieleski (2016) argued that entrepreneurs' lower stress levels are attributable to above-average psychological capital and the alignment of their competencies with the demands of the entrepreneurial environment, referencing Schneider's ASA (Attraction–Selection–Attrition) theory and the concept of social capital (Luthans et al., 2007).

Schneider's ASA theory posits that individuals with high tolerance and coping abilities for stress are more likely to thrive in entrepreneurial environments. This predisposition is linked to high social capital, comprising self-efficacy, optimism, hope, and mental resilience, which is negatively correlated with stress, particularly among mature entrepreneurs (Baron et al., 2016). The theory also explains similarities in skills and preferences among organisational members and individual career choices, as people seek environments that facilitate personal goals and values. The entrepreneurial environment is attractive due to its autonomy, but it imposes high demands, including risk, time pressure, responsibility, and stress. These work characteristics may serve as push-out factors. Persistent exposure to them can deplete resilience resources, leading entrepreneurs to reconsider their career path (Gilboa et al., 2008; Fine et al., 2012).

In Poland, research on stress levels among small business owners (up to nine employees), rank-and-file employees, and managers revealed no significant differences (Basińska, 2011). All groups reported moderate stress levels. Further studies by Bajer (2016) found that micro-entrepreneurs exhibited higher stress in dimensions such as burden, threat, responsibility, and lack of support, compared to full-time employees.

## 3. Fear of Failure in Business

Fear of failure is a critical determinant of entrepreneurs' psychological functioning, influencing the level of stress experienced when facing business challenges, daily decision-making, and relationships with stakeholders. Fear of failure and bankruptcy can inhibit the creation of new businesses and is frequently cited as a reason for postponing entrepreneurial ventures. In Poland, nearly 60

Psychologically, fear of failure encompasses both environmental and internal factors. While fear is a response to identifiable threats, anxiety is more abstract and internal, manifesting as a sense of danger with a hidden source (Kępiński, 2012). The fear of business failure is part of a broader phenomenon linked to achievement motivation. Murray (1938) defined the need for achievement as the desire to overcome obstacles and perform challenging tasks efficiently. Atkinson (1957) further established that the need for success and the need to avoid failure are equally important and strongly correlated; an avoidance tendency emerges when the desire to avoid failure outweighs the drive for success.

For many years, it was believed that fear of failure serves as a drive to avoid fiasco and embarrassment. This simplified view is not valid anymore. Conroy (2001) expanded the concept of fear of failure, identifying its multidimensional nature: fear of shame and embarrassment, fear of diminished self-esteem, fear of an uncertain future, fear of losing the interest of significant others, and fear of causing their dissatisfaction. These aspects are particularly relevant to entrepreneurs, as business failure may result in all these consequences.

## 4. Psychological Resources

Contemporary positive psychology and health psychology emphasise the importance of personal resources—such as hope, self-esteem, and self-efficacy—as factors promoting mental health and resilience to stressors.

Hope has been the subject of psychological research for several decades. It is commonly perceived as an important aspect of human internal functioning (Trzebińska, 2008; Trzebiński & Zięba, 2003) and a relatively stable element of self-concept. Research indicates that it is a construct distinct from optimism and self-efficacy (Łaguna et al., 2005). Hope, as conceptualised by Snyder (2002), is a positive motivational state focused on goals and strategies to achieve them, characterised by the expectation of success despite obstacles (willpower) and the belief in one's competence to find solutions.

In their 2007 study, Hmieleski and Carr posited that the phenomenon of hope functions as a psychological buffer, thereby mitigating the adverse effects of entrepreneurial working conditions on individuals' well-being, ultimately fostering a more favourable appraisal of life. Bailey et al. (2007) also identified hope as a predictor of psychological strength and life satisfaction. High hope for success correlates with better adaptation and mental health, and interventions to increase hope have been shown to improve mood (Łaguna et al., 2005; Bailey et al., 2007; Hmieleski & Carr, 2007).

Self-esteem, a relatively stable subjective construct in adults, is a global self-assessment that influences perseverance, coping with adversity, and resilience to failure or severe stress (Baumeister et al., 2003; Rosenberg, 1965; Tesser, 1999).

High self-esteem is expressed through positive and accepting judgments about oneself. Individuals with high self-esteem perceive their behaviour in a positive light, anticipate more positive consequences of their actions than those of others, remember information about their own successes better than failures, interpret ambiguous messages as positive rather than negative, and perceive their own strengths as more unique and their weaknesses as more common. They also regard their own attributes and fields of interest as particularly significant (Ehrlinger& Dunning, 2003). Individuals possessing elevated self-esteem exhibit pronounced perseverance in the pursuit of their objectives, demonstrate a tendency to minimise the impact of adversity, and enhance their efforts in anticipation of successful outcomes. Such individuals are more likely to interpret challenges as opportunities for growth and remain steadfast in their commitment to achieving set goals.

As articulated by M. Rosenberg (1965; as cited in Dzwonkowska et al., 2008), elevated self-esteem is characterised by an individual's conviction that they are sufficiently worthy and valuable in their own regard. Empirical findings derived from the Rosenberg Self-Esteem Scale (SES), demonstrate positive correlations with various psychological constructs, including reported levels of happiness, positive affect, optimism, extraversion, internal locus of control, and generalised self-efficacy (Mar et al., 2006). Furthermore, A. Tesser (1999) underscored the significance of self-esteem as a determinant of psychological well-being and mental resilience.

Self-efficacy, derived from Bandura's social learning theory (2007), is considered one of the most vital personal resources for achievement and mental resilience.

Self-efficacy refers to an individual's belief in their capacity to perform specific behaviours. It encompasses a subjective evaluation of one's own competencies and plays a crucial role in shaping how individuals think, feel, behave, and motivate themselves towards action. It shapes behaviour, motivation, and coping strategies, and is a better predictor of goal setting and attainment than self-esteem.

An individual's robust sense of self-efficacy significantly shapes their potential for achievement and overall well-being, as it enhances their propensity to embrace challenges rather than perceive them as threats to be circumvented. Those who possess confidence in their capacity to exert influence over events are inclined to establish ambitious objectives, demonstrate unwavering commitment to their attainment, and intensify their efforts when confronted with the prospect or reality of failure. Conversely, individuals with diminished self-efficacy tend to evade challenging tasks, establish modest expectations, and demonstrate limited engagement in the pursuit of their objectives. When confronted with adversity, such individuals are more prone to concentrate on perceived personal inadequacies rather than to adopt effective problem-solving strategies, thereby increasing their vulnerability to stress and depressive symptoms. Individuals exhibiting low levels of this trait tend to overestimate the probability of failure, which adversely affects their emotional well-being, manifesting in heightened stress and diminished task performance.

## 5. Financial Resources

Financial difficulties and business failures substantially diminish psychological comfort and may lead to depression, withdrawal from business activity, and even severe outcomes such as suicidal tendencies (Pollack et al., 2012; McDaid et al., 2013; Smith & McElwee, 2011; Weller, 2012). Chronic stress from financial instability, work overload, and responsibility for others further exacerbates these risks (Baron et al., 2016).

Longitudinal research by Gorgievski, Bakker, and Schaufeli (2010) among agricultural business owners revealed that declines in production and profits were the primary sources of stress, leading to intentions to close businesses and a negative spiral of worsening financial assessment and increased stress. Anticipation of resource loss triggers cycles of psychological costs, including diminished self-esteem, self-efficacy, and hope (Gorgievski& Hobfoll, 2008; Hobfoll, 2001).

Entrepreneurial activity is inherently profit-oriented, with income and its growth serving as objective indicators of effectiveness. Profitability not only reflects economic competence but also yields psychological benefits, such as satisfaction and respect within the economic environment (Lechat and Torres, 2017). The attainment of satisfactory profits is indicative of broad economic competence and reflects the success of the entire entrepreneurial process. This encompasses accurate market assessment, appropriate selection of business domain, choice of partners, collaborators, and employees, as well as effective management of opportunities and threats. Robust financial performance enables further development, investment, and profit generation, and additionally serves as a source of satisfaction and respect within the economic community. The generation of profits from entrepreneurial activity is pivotal in providing financial support not only for the entrepreneur themselves, but also for their dependents.

Equally significant as the objective quantification of income is its subjective appraisal, specifically the degree of satisfaction derived from one's income. Psychological theories of utility, as articulated by Zaleśkiewicz (2015), explore the processes underpinning the evaluation of attained outcomes. Within this framework, utility is shaped by an individual's current circumstances, hierarchical goal structure, and constellation of needs. The perceived worth of economic achievements or possessions is thus influenced not solely by their objective magnitude, but also by the nature and intensity of the needs experienced at a given time. For example, when material deficits remain unaddressed despite a particular level of financial resources, the utility ascribed to that sum is diminished relative to situations in which such deficits are alleviated. Accordingly, the subjective value of financial resources is determined by their efficacy in fulfilling essential needs and facilitating the attainment of personal objectives. It follows that the degree to which material needs are satisfied ought to be considered a crucial dimension of overall well-being.

The association between income levels, their fluctuations and the subjective financial satisfaction experienced by entrepreneurs is likely influenced by a variety of additional subjective determinants (such as gender, individual aspirations, and personality traits), as well as situational variables (including the comparative performance of other actors within the social milieu and the availability of alternative resources that may mitigate the impact of present financial losses or gains).

In light of these considerations, it is justified to distinguish between the constructs of absolute income, income growth, income decline, and income satisfaction. These categories represent some of the most salient indicators of entrepreneurial success, particularly in view of the primary objectives underpinning the existence of a business enterprise.

Financial difficulties and entrepreneurial failures substantially diminish psychological well-being and may even lead to depression, resulting in withdrawal from business activity (Pollack et al., 2012). Research by McDaid et al. (2013) confirms the association between financial hardship and negative outcomes such as anxiety, stress, depression, deterioration of physical health, and suicidal tendencies among entrepreneurs. Smith and McElwee (2011) further demonstrated that shame and guilt associated with financial failure can lead to alcoholism, psychotic disorders, and suicide. Such experiences also cause mental exhaustion and impair the ability to recover psychological strength (Weller, 2012). These risks are particularly pronounced among individuals whose stress arises from a fast work pace, volatility and unpredictability of events, work overload, and responsibility for others (Baron et al., 2016).

Entrepreneurs who operate their businesses for extended periods under heightened psychological stress tend to achieve poorer financial outcomes (Gorgievski et al., 2010). In pursuit of improved economic circumstances for themselves and their companies, they often jeopardise their health by working excessively long hours without respite (Cardon and Patel, 2015).

Gorgievski, Bakker, and Schaufeli (2010) conducted longitudinal research among 260 agricultural business owners to examine the relationship between company financial status and psychological stress. The authors investigated the extent to which an objectively unfavourable financial situation influences intentions to close the business and induces stress. The theoretical framework for this analysis was Hobfoll's (2006) Conservation of Resources (COR) theory, which posits that the central human need is to protect and enhance one's resources, and that resource loss leads to stress, particularly when primary resources essential for survival are threatened. Loss of certain resources prompts individuals to mobilise others to acquire new assets or compensate for the loss. Simultaneously, psychological mechanisms exist to maintain emotional equilibrium and stability. Therefore, stress resulting from resource loss (e.g., financial) can be regulated by these internal mechanisms, stabilising well-being at a constant level.

Structural equation modelling (Gorgievski et al., 2010) revealed that the principal source of stress among agricultural entrepreneurs was a decline in production and company profits. Psychological stress increased the tendency to close businesses and, over time, initiated a negative spiral: heightened stress led to a more pessimistic assessment of the financial situation, regardless of objective indicators, thereby intensifying stress through a self-fulfilling prophecy. Thus, the perceived severity of financial difficulties predicts stress and intentions to close the business, which in turn exacerbates psychological discomfort, as business liquidation entails further economic losses. Anticipation of resource loss induces stress, triggering cycles of psychological costs—additional losses in fundamental resources such as self-esteem, self-efficacy, and hope (Gorgievski and Hobfoll, 2008; Hobfoll, 2001).

## 6. Research objectives and hypotheses

This study aims to establish whether there are associations between psychological resources, such as hope for success, self-esteem and self-efficacy, and financial resources. This will be examined in relation to objective and subjective indicators of business success and the psychological stress and fear of failure experienced by entrepreneurs. To explore these dynamics more nuanced, analytical models examining the relationships between the variables will be employed. This will enable us to identify key predictors of psychological stress among entrepreneurs. Drawing upon the aforementioned theoretical foundations and empirical findings from research conducted with entrepreneurial populations, the following hypotheses have been formulated:

Hypothesis 1: Psychological stress associated with business operations and fear of failure are contingent upon the psychological resources possessed by entrepreneurs. Specifically, higher levels of hope for success, self-esteem, and self-efficacy are inversely related to psychological stress and fear of failure in the entrepreneurial context.

Hypothesis 2: The financial and material resources of entrepreneurs are hypothesised to be associated with the degree of stress and fear of failure encountered. Greater income, positive income growth, a favourable income level compared to a reference group, income stability, satisfaction with income and the overall financial situation, as well as wealth perceived as superior to that of the reference group, are all anticipated to correspond with reduced psychological stress and fear of failure in business.

Hypothesis 3: Psychological resources—namely hope for success, self-efficacy, and self-esteem are predictors of stress levels among entrepreneurs.

Hypothesis 4: Financial and material resources serve as predictors of the psychological stress experienced by entrepreneurs.

## 7. Material and methods

Group under the study

The study sample comprised entrepreneurs who owned either newly established businesses (enterprises registered for up to 42 months, hereafter referred to as young or new entrepreneurs) or more established ventures (those registered for more than 42 months, hereafter referred to as mature or experienced entrepreneurs). In total, 349 participants were surveyed, of whom 155 were classified as new entrepreneurs and 194 as mature entrepreneurs. The cohort encompassed both self-employed individuals and representatives from the micro-enterprise sector (businesses employing fewer than ten people), as well as small enterprises (those with between ten and fifty employees). Distinguishing entrepreneurs as mature and young is consistent with the research methodology presented in GEM Poland (Global Entrepreneurship Monitor) reports (Tarnawa et al., 2025). The period of three and a half years is considered a milestone in business activity. Surviving this period indicates the success of the first stage, which is setting up the business and moving on to the next stage, which is managing an existing company.

Within the sample, 45.6% of participants were women and 54.4% were men. Women constituted 47.7% of the young entrepreneur subgroup and 43.8% of the mature entrepreneur subgroup. The mean age of the entrepreneurs was 39.24 years, with half of the sample aged 38 years or older. Among young entrepreneurs, the mean age was just under 31 years and the median age was 28 years, whereas for mature entrepreneurs, the mean and median ages were approximately 46 and 47 years, respectively. The average daily working time reported by entrepreneurs was 8.62 hours, with mature entrepreneurs working longer hours on average (M = 8.82, SD = 2.01) compared to their younger counterparts (M = 8.36, SD = 1.96). The selection of participants for the sample was purposeful, using the ‘snowball’ method. This should be taken into account when interpreting the results.

## 8. Procedure and methods

The study was cross-sectional in nature and voluntary, using self-report measures. Participants were informed of the study’s purpose and consented to participate.

The following tools were used:

1. Self-Esteem Scale (SES): The SES Self-Esteem Scale by M. Rosenberg, adapted by Dzwonkowska, Lachowicz-Tabaczek and Łaguna (2008), is an indicator of overall self-esteem. Self-esteem is treated as a relatively stable trait rather than a temporary state. ‘People with high self-esteem experience fewer negative emotions, including anxiety, sadness and depression, than those with low self-esteem. In addition, they are more active and socially adept, and demonstrate a higher level of disposition conducive to effective task performance.’ The scale consists of 10 statements. The respondent is asked to indicate the extent to which they agree with each of them. The answer is given on a four-point scale, from 1 – strongly agree to 4 – strongly disagree. The results range from 10 to 40 points, with a higher score indicating higher self-esteem. The reliability coefficient (Cronbach’s alpha) of the Polish version of the method in the various groups studied ranges from 0.81 to 0.83. The split-half reliability for even and odd statements is 0.75, and the inter-half correlation coefficient is 0.62. The satisfactory stability of the tool has also been proven. Exploratory and confirmatory factor analysis confirmed the validity of the SES scale. This scale correlates sufficiently highly with other scales measuring self-esteem (Łaguna, Lachowicz-Tabaczek, Dzwonkowska, 2007).

2. Generalised Self-Efficacy Scale (GSES) developed Schwarz and Jerusalem, andadapted by Juczyński (2000). The score is an indicator of the belief in one’s own effectiveness as a business owner. The scale consists of 10 statements that relate to an individual’s general beliefs about their ability to handle difficulties and obstacles. The respondent is asked to respond to each statement by choosing one answer on a four-point scale from 1 - no, not true to 4 - yes, completely true. The sum of all ratings provides an indicator of self-efficacy (in the role of an entrepreneur). The higher the total score, the greater the belief in one’s own effectiveness. Cronbach’s alpha coefficient is 0.85. The reliability of the scale assessed using the test-retest method (after five weeks) is 0.78.

3. Hope for Success Questionnaire (KNS) developed by Snyder, and adapted into Polish by Łaguna, Trzebiński and Zięba (2005) is an indicator of hope for achieving success, that is, a person’s belief that they are able to find a way to reach their goal and can mobilize their forces to accomplish it. The scale consists of 12 questions (8 diagnostic), to which respondents answer on an eight-point scale (from 1 - definitely untrue to 8 - definitely true). The KNS allows for the assessment of two dimensions of hope (belief in having the willpower to achieve goals and belief in having the skills to find solutions in difficult situations), as well as its overall level. The reliability of the overall KNS score, estimated by Cronbach’s alpha coefficient, is 0.82. The

reliability of the willpower belief scale is 0.74, and for the problem-solving belief scale, the reliability coefficient is 0.72. KNS is characterized by satisfactory accuracy. KNS results positively correlate with the following personality variables: basic hope, optimism, self-efficacy, and overall self-esteem, as well as with extraversion and conscientiousness, and negatively with anxiety, depression, and neuroticism (Łaguna, Trzebiński, Zięba, 2005).

4. Perceived Stress Scale PSS-10 developed by Cohen, Kamarcka, Mermeinstein, adapted into Polish by Juczyński and Ogińska-Bulik (2009) It is an indicator of the level of stress associated with running a business (professional activity). The scale contains 10 questions regarding various subjective feelings related to personal problems and events, behaviors, and coping strategies. Respondents were asked to consider the context of running a business (non-entrepreneurs were asked to consider their professional activity) when answering. Responses are marked on a five-point scale from 0 – never to 4 – very often. The PSS-10 score reflects the subjective assessment of one's own stress symptoms resulting from experienced events and is a measure of chronic stress. The higher the score, the greater the intensity of the perceived stress. Internal consistency was checked, for which a Cronbach's alpha of 0.86 was obtained. Reliability determined based on repeated testing over a 2-day interval was 0.90, and over a 4-week interval 0.72. Validity was estimated by correlating PSS-10 results with the severity of occupational stress at work (Questionnaire for Subjective Assessment of Work), with scores measured using the COPE scale, Rosenberg's SES, Schwarzer's GSES, and others. The results indicated the validity of the PSS-10 (Juczyński, Ogińska-Bulik, 2009).

5. The questionnaire developed by the author covering following topics:

- intensity of fear of failure (the respondent is asked to estimate their fear of failure on a five-point scale (from 1 – very low fear of failure to 5 – very high fear of failure)
- sociodemographic data (age, gender, length of time in business).
- selected financial resources :
  a. income: income estimated in relation to the national average, seven-point scale (from 0 – significantly less than the national average to 6 – approximately five times the national average or more);
  b. estimated income compared to the reference group: five-point Likert scale (from 1 – significantly lower income to 5 – significantly higher income);
  c. decrease/increase in income: five-point Likert scale (from 1 – very low increase/decrease in income to 5 – very high increase/decrease in income);
  d. satisfaction with income: five-point Likert scale (from 1 – very low satisfaction with income to 5 – very high satisfaction with income);
  e. satisfaction with wealth: five-point Likert scale (from 1 – very low satisfaction with wealth to 5 – very high satisfaction with wealth);
  f. wealth estimated in comparison to the reference group: five-point Likert scale (from 1 – significantly lower wealth to 5 – significantly higher wealth),
  g. income stability (certainty): seven-point Likert scale (from 1 – minimum income certainty/stability to 7 – maximum income certainty/stability);
  h. satisfaction with fulfilement of material needs: seven-point Likert scale (from 1 – minimum degree of satisfaction with fulfilement of material needs to 7 – maximum degree of satisfaction with fulfilement of material needs ).

## 9. Results

Statistical calculations were performed using the IBM SPSS 25 statistical package. The following statistical analyses were applied: Pearson's r correlation analysis and stepwise forward linear regression.

To verify hypothesis 1 the seria of Pearson's correlation analyses was performed. The results of these analyses are presented in Table 1.

TABLE 1. Results of the analysis of the correlation between stress and fear of failure and the psychological resources of entrepreneurs

| | Hope for success – the ability to find solutions | Hope for success – willpower | Self-efficacy belief | Self-esteem |
|---|---|---|---|---|
| Entrepreneurs entire group | | | | |
| Stress | -0,36** | -0,54*** | -0,41*** | -0,47*** |
| Fear of failure | -0,41*** | -0,51*** | -0,46*** | -0,68*** |
| Young entrepreneurs | | | | |
| Stress | -0,40** | -0,64*** | -0,35** | -0,57*** |
| Fear of failure | -0,39*** | -0,55*** | -0,43*** | -0,68*** |
| Mature entrepreneurs | | | | |
| Stress | -0,17 | -0,27* | -0,42** | -0,19* |
| Fear of failure | -0,26 | -0,25* | -0,44*** | -0,21* |

The table shows Pearson's linear correlation coefficient (r) *p<0.05; **p<0.01; ***p<0.001

Source: own calculations.

The findings demonstrate that both the stress experienced by entrepreneurs and their fear of failure in business exhibit significant negative associations with psychological resources such as hope for success (encompassing both the belief in one's capacity to identify solutions and the aspect of willpower—i.e., determination in goal pursuit—as well as self-efficacy and self-esteem). Among young entrepreneurs, the intensity of stress is most strongly correlated with hope for success in terms of willpower (r = -0.64***) and self-esteem (r = -0.57***). Additionally, the ability to find solutions is significantly related to stress within this cohort (r = -0.40**).

In contrast, among mature entrepreneurs, the associations between psychological resources and stress are notably weaker. Significant relationships were observed for self-efficacy (r = -0.40**), hope for success in the aspect of strong will (r = -0.27*), and self-esteem (r = -0.19*), while the ability to find solutions did not demonstrate a significant association with stress in this group.

It is noteworthy that the relationships identified within the cohort of young entrepreneurs are both stronger and more numerous than those observed among mature entrepreneurs. The sole exception is self-efficacy, which demonstrates a stronger association with stress in mature entrepreneurs compared to their younger counterparts (r = -0.44** and r = -0.35**, respectively).

A similar pattern emerges in the context of psychological resources and fear of failure. Among entrepreneurs with less business experience, all Pearson's r correlation coefficients between subjective psychological resources and fear of failure are significant and range from moderate to high in strength: self-esteem (r = -0.68***), hope for success in the aspect of strong will (r = -0.55***), self-efficacy (r = -0.43***), and hope for success in the aspect of finding solutions (r = -0.39***). Conversely, within the group of entrepreneurs with more extensive experience, fear of failure is significantly and moderately associated with self-efficacy (r = -0.44***), while other correlations are considerably weaker (hope for success in terms of finding solutions, r = -0.26; hope for success in terms of strong will, r = -0.25*; and self-esteem, r = -0.21*).

Hypothesis 1, which posited the existence of significant associations between psychological resources and the intensity of stress and fear of failure among entrepreneurs—both in general and when differentiated by entrepreneurial experience—was largely substantiated. Nevertheless, a detailed examination of these associations reveals distinct characteristics within the identified subgroups.

The subsequent stage involved the examination of hypothesis 2, which posits that both objective and subjective dimensions of financial and material status are related to the levels of stress and fear of failure experienced by entrepreneurs. Specifically, it was hypothesised that higher income, greater increases in income, superior income levels relative to a reference group, enhanced income stability, increased satisfaction with income and material position, as well as greater wealth compared to the reference group, would be associated with reduced psychological stress and diminished fear of failure within the business context.

Table 2. Results of the correlation analysis between stress and fear of failure and the financial and material aspects of entrepreneurs' situation.

| | Entrepreneurs entire group | | Young entrepreneu | | Mature entrepreneurss | |
|---|---|---|---|---|---|---|
| | Stress | Fear of failure | Stress | Fear of failure | Stress | Fear of failure |
| Degree of satisfaction of material needs | -0,25* | -0,25** | -0,21* | -0,19 | -0,26* | -0,23* |
| Income level compared to the reference group | -0,43*** | -0,27* | -0,48* | -0,28* | -0,21* | -0,25* |
| Income | -0,60*** | -0,51** | -0,60*** | -0,43*** | -0,55*** | -0,52*** |
| Income stability | -0,49** | -0,57** | -0,38** | -0,31* | -0,50*** | -0,60*** |
| Income growth | -0,49*** | -0,66*** | -0,54*** | -0,33* | -0,46*** | -0,67*** |
| Wealth compared to the reference group | -0,13 | -0,23* | -0,09 | 0,04 | -0,12 | -0,25* |
| Satisfaction with income | -0,49*** | -0,42*** | -0,31** | 0,40*** | -0,31** | -0,44*** |
| Satisfaction with wealth | -0,14 | -0,21* | -0,11 | -0,25* | -0,13 | -0,02 |

The table shows Spearman's rho correlation coefficient. *p<0.05; **p<0.01; ***p<0.001

Source: own calculations.

The most significant financial correlates of stress among young entrepreneurs are as follows: income (Spearman's rho = -0.60, p<0.001), income growth (rho=-0.54, p<0.001), income level relative to the reference group (rho=-0.48, p<0.001 ), and income stability (rho=-0.38, p<0.05). Conversely, in the cohort of mature entrepreneurs, the strongest correlates are: income level ( rho=-0.55, p<0.001), income stability (rho=0.50, p<0.001), and income growth (rho=-0.46, p<0.001). Variables pertaining to entrepreneurs' wealth do not exhibit a significant association with stress levels or demonstrate only a weak relationship.

Comparable findings were observed concerning the relationship between financial and asset resources and fear of failure. For young entrepreneurs, the principal correlates were: income (rho=-0.43, p<0.001), satisfaction with income (rho=-0.40, p<0.001), income growth (-rho=0.33), and income stability (certainty) (rho=-0.31, p<0.001). In the mature entrepreneur group, these included: income growth (rho=-0.67, p<0.001), income stability (rho=-0.60, p<0.001 ), income size (rho=-0.52, p<0.001), and income satisfaction ( rho=-0.44, p<0.001 ).

The correlation analysis presented indicates that the financial situation of entrepreneurs is a factor significantly associated with their psychological well-being, specifically in terms of stress and fear of failure. Hypothesis 2 was thus supported, albeit not all indicators of financial status reached statistical significance.

In order to verify hypothesis 3, which assumed that psychological resources – hope for success, self-efficacy and self-esteem are predictors of stress among entrepreneurs, a linear regression (stepwise forward linear regression) was performed. The results are presented in Table 3.

TABLE 3. Results of linear regression analysis for relationship between psychological resources and stress

| | B | SE(B) | Beta | t | p | r | $r_{cz}$ | VIF |
|---|---|---|---|---|---|---|---|---|
| Young entrepreneurs | | | | | | | | |
| Intercept | 34,317 | 5,809 | | 5,908 | <0,001* | | | |
| Hope for success - willpower | -0,450 | 0,071 | 0,471 | 6,366 | <0,001* | 0,672 | 0,461 | 1,699 |
| Self-esteem | -0,259 | 0,095 | -0,178 | -2,731 | 0,007* | -0,476 | -0,218 | 1,328 |
| Hope for success - the ability to find solutions | -0,293 | 0,122 | -0,164 | -2,399 | 0,018* | -0,501 | -0,192 | 1,455 |
| Self-efficacy belief | -0,181 | 0,079 | -0,133 | -2,298 | 0,023* | -0,254 | -0,184 | 1,037 |
| Test F | F(4;150)=40,209; p<0,001* | | | | | | | |
| $R^2_{sk}$ | 0,39 | | | | | | | |
| Mature entrepreneurss | | | | | | | | |
| Intercept | 23,568 | 4,829 | | 4,880 | <0,001* | | | |
| Self-efficacy belief | -0,480 | 0,081 | 0,412 | 5,907 | <0,001* | 0,496 | 0,394 | 1,269 |
| Hope for success - willpower | -0,480 | 0,081 | 0,412 | 5,907 | <0,001* | 0,496 | 0,394 | 1,269 |
| Test F | F(2;190)=35,531; p<0,001* | | | | | | | |
| $R^2_{sk}$ | 0,267 | | | | | | | |

Description stepwise forward linear regression:, Linear regression, stepwise method, was used. B— regression coefficient, SE(B)— regression coefficient estimation error, Beta— standardised regression coefficient, t— t-statistic value in the model parameter significance test, p— probability in the t or F test, r— Pearson's linear correlation coefficient, rcz— partial correlation coefficient, F— F-test for the significance of the coefficient of determination in the population, R2 = coefficient of determination from the sample.

Source: own calculations.

All of the subjective resources under examination were incorporated into the regression models analysing psychological stress. The model evaluated for the cohort of young entrepreneurs indicated that psychological resources account for nearly 40% of the variance in stress experienced within business contexts. The principal determinants identified were hope for success (willpower), self-esteem, and, once again, hope for success with respect to problem-solving abilities. In contrast, the model assessed for mature entrepreneurs demonstrated a comparatively diminished influence of theselected subjective variables on the level of stress encountered. Among this group, two characteristics—self-efficacy and hope for success related to strong wil—were found to be significant, collectively explaining approximately 27

The next step was to verify hypothesis 4, according to which selected financial and asset aspects are predictors of stress among entrepreneurs. It was expected that the wealth of entrepreneurs— both financial and material— would alleviate the intensity of stress to some extent. Indeed, when analysing the results of entrepreneurs (separately for the group of new and mature entrepreneurs), it can be seen that some of the financial aspects have a significant impact on the stress associated with running a business.

The subsequent phase involved testing hypothesis 4, which posited that selected financial and asset-related factors serve as predictors of stress among entrepreneurs. It was hypothesised that the wealth of entrepreneurs–encompassing both financial and material assets–would, to some extent, mitigate the intensity of stress experienced. Upon examining the results for entrepreneurs, distinguished by new and mature cohorts, it was observed that certain financial aspects exert a statistically significant relations to stress associated with business operations.

TABLE 4. Results of the estimation of the stress model for young entrepreneurs: the role of financial and property aspects

| | B | SE(B) | Beta | t | p | r | $r_{cz}$ |
|---|---|---|---|---|---|---|---|
| Young entrepreneurs | | | | | | | |
| Intercept | 42,634 | 1,586 | | 19,272 | <0,001 | | |
| Income | -1,474 | 0,541 | -0,465 | -4,892 | <0,001 | -0,757 | -0,378 |
| Income growth | -1,123 | 1,342 | -0,323 | -4,002 | <0,001 | -0,568 | -0,534 |
| Income level compared to the reference group | -0,933 | 0,248 | -0,226 | -4,097 | <0,00 | -0,268 | -0,216 |
| Satisfaction with income | -0,415 | 0,179 | -0,119 | -2,153 | 0,032 | -0,198 | -0,116 |
| Test F F(3;151)=16,099; p<0,001* | | | | | | | |
| $R^2_{sk}$ 0,196 | | | | | | | |
| Mature entrepreneurss | | | | | | | |
| Constant | 24,352 | 2,596 | | 9,380 | <0,001 | | |
| Income | -1,933 | 0,428 | -0,226 | -4,097 | <0,001 | -0,468 | -0,516 |
| Income stability | -1,015 | 0,235 | -0,119 | -2,153 | <0,001 | -0,398 | -0,454 |
| Income growth | -0,945 | 0,231 | -0,182 | -2,087 | 0,032 | -0,342 | -0,231 |
| Satisfaction with income | -0,471 | 0,198 | -0,187 | -1,87 | 0,029 | -0,231 | -0,212 |
| Test F F(2;189)=7,781; p=0,001* | | | | | | | |
| $R^2_{sk}$ 0,156 | | | | | | | |

Description: as in table 3

Source: own calculations.

The experience of stress associated with business operations among mature entrepreneurs is, ceteris paribus, primarily determined by financial factors, which account for over 15% of the variance in stress levels. In contrast, for young entrepreneurs, the regression model accounts for almost 20% of the variance in experienced stress. In both groups, income level emerges as a major determinant of stress. However, in the case of young entrepreneurs, additional significant predictors include income growth over the preceding 12 months, comparative income assessments, income stability (certainty), and satisfaction with income. For mature entrepreneurs, the principal factors influencing psychological stress are income level, income stability, income growth, and income satisfaction. It is noteworthy that, in both models, variables such as wealth, wealth satisfaction, and wealth assessment through comparison with a reference group did not demonstrate significant predictive value for stress. Furthermore, for mature entrepreneurs, comparative income evaluation relative to a reference group was also found to be insignificant, in contrast to its relevance among young entrepreneurs.

## 10. DISCUSSION

The findings from the correlation and regression analyses concerning entrepreneurs' stress, fear of failure, and both psychological and financial resources generally align with theoretical expectations. The association between entrepreneurial stress and financial circumstances has already been explored in psychological research. Empirical evidence indicates that lower business income is correlated with heightened stress and adverse effects on mental well-being (Anderson and Hughes, 2010; D'Angelo et al., 2016; Kwon and Sohn, 2017). Entrepreneurs themselves frequently identify financial difficulties as a principal source of stress (Lechat and Torrès, 2016). Further, it has been demonstrated that entrepreneurs experiencing elevated psychological stress tend to achieve inferior financial outcomes (Baron et al., 2016; Gorgievski et al., 2010).

The data analyses highlight the considerable significance of psychological resources—surpassing that of financial and material assets. Within the psychological literature, these variables are collectively termed as psychological capital, encompassing hope for success, self-efficacy, and self-esteem. Notably, the regression models reveal differences between young and experienced entrepreneurs: among the former, positive self-perceptions (psychological resources) emerge as more potent determinants of stress than among the latter group. It may be inferred that psychological capital assumes a particularly salient role during the nascent phases of entrepreneurship, equipping individuals to assume risks and undertake intensive entrepreneurial endeavours. To some extent, psychological capital also serves to buffer entrepreneurs against the detrimental effects of operating in psychologically demanding environments. Moreover, positive self-belief exerts a substantial influence on both the intention to initiate a business and the execution of entrepreneurial decisions (Łaguna, 2010). The results of our own research correspond with the findings of other researchers investigating the links between stress in business, psychological capital, and entrepreneurial performance. For example, a study conducted by Atiglah and Addai (2023) showed that moderate psychological stress promotes better economic outcomes, but only when entrepreneurs have sufficiently high psychological capital. This, in turn, contributes to greater resilience in the face of uncertainty and crises, which are an inherent part of running a business (Hwank, 2024).

According to the ASA framework (Schneider et al., 1995), individuals with an elevated capacity for managing stress are more likely to function effectively within entrepreneurial contexts. This capacity is associated with the high social capital characteristic of this cohort—a synthesis of self-efficacy, optimism, hope, and psychological resilience. Baron et al. (2016) observed a negative correlation between high social capital and stress, particularly among mature entrepreneurs. The present research similarly confirms such associations, though these were found to be more pronounced among young business owners.

It is important to acknowledge that the average age of young entrepreneurs in the sample is 31 years, compared to 46 years for mature entrepreneurs, which may partially account for the observed differences in stress conditions. Distinct life stages are inherently linked to variations in stress resilience, experience, and competencies acquired through development. Furthermore, the research model employed did not incorporate other salient determinants of psychological resilience, such as emotional stability or health status. Nor did it control for stressors endemic to the business environment (e.g., working under time pressure, making high-stakes business decisions, operating amid uncertainty, the inherent difficulty of tasks, and intense market competition).

In conclusion, the findings of this study support the division of the entrepreneurial sample into two cohorts based on business experience (up to 42 months and over 42 months). Psychological resources—specifically, hope for success (with particular emphasis on the volitional component), self-esteem, and perceived self-efficacy—demonstrate significant associations with experienced stress and fear of failure. The results indicate that these psychological resources function as determinants of psychological stress. Importantly, psychological capital is recognised as a construct amenable to enhancement through targeted psychological interventions (Mockałło and Stachura-Krzyształowicz, 2021). Such interventions represent an increasingly prevalent challenge for organisations committed to fostering employee well-being in the workplace. Moreover, the development of psychological resources has been shown to augment both the effectiveness and efficiency of work performance. In light of the present research findings, it is recommended that entrepreneurs actively invest in the development of personal resources to mitigate the psychological costs associated with business operations and to optimise financial outcomes.

The presented research has limitations. Some of them are quite typical for studies conducted using self-report measurement methods and correlational analyses. Others, in turn, relate to the method of selecting the study group. During the research, it was only possible to obtain data from those entrepreneurs who agreed to participate and demonstrated significant perseverance (completing the survey and psychological tools took about 20 minutes). Some respondents completed only part of the tools provided to them, while others refused to participate in the study altogether. It is also worth noting that among the surveyed entrepreneurs, the majority were owners of small businesses, and their situation differs significantly from that of owners of large companies, who most often delegate a range of responsibilities to subordinate managers. They also have greater resources, which can facilitate their daily functioning and coping with stress. What limits the ability to generalize the obtained results is the method of selection for the study group (purposive sampling and the "snowball" method). Furthermore, the presented study did not take into account gender, which is an important variable related to experiencing stress in business and fear of failure (Biegańska, 2017).

Research on stress in business and the predispositions of entrepreneurs will be continued due to their importance and practical significance.

## References


[1] Atiglah, L., Addai, S.P. (2023). *Evaluating entrepreneurial stress and its effect on business success and survival. A case study of selected small-scale entrepreneurs in Adum-Kumasi*. DOI: https://doi.org/10.13140/RG.2.2.16790.56642

[2] Andersson, P. (2008). *Happiness and health: Well-being among the self-employed*. The Journal of Socio-Economics 37, 213–236.

[3] Atkinson, J. W. (1957). *Motivational determinants of risk taking behavior*. Psychological Review 64, 359–372.

[4] Bajer, E. (2016). *Działania przedsiębiorcze, postawy wobec pracy i ocena nasilenia stresu u mikroprzedsiębiorców i pracowników etatowych*. Psychologia Społeczna 11(1), 36, 84–97.

[5] Bandura, A. (2007). *Teoria społecznego uczenia się*. Warszawa: Polskie Wydawnictwo Ekonomiczne.

[6] Baron, R. A. (2013). *Enhancing entrepreneurial excellence: Tools for making the possible real*. Cheltenham, UK: Edward Elgar.

[7] Baron, R. A., Franklin, R. J., Hmieleski, K. M. (2016). *Why entrepreneurs often experience low, not high levels of stress: The joint effects of selection and psychological capital*. Journal of Management 42(3), 742–768.

[8] Basińska, B. (2005). *Warunki pracy a źródła stresu właścicieli małych przedsiębiorstw*. W: D. Walczak-Duraj (red.), Humanizacja pracy wobec wyzwań transformacyjnych i cywilizacyjnych (s. 205–221). Płock: Wydawnictwo Naukowe Novum.

[9] Baumeister, R. F., Campbell, J. D., Krueger, J. I.,Vohs, K. D. (2003). *Does high self-esteem cause better performance, interpersonal success, happiness, or healthier lifestyles?* Psychological Science in the Public Interest, 4(1), 1–44.

[10] Biegańska, K (2017). *Strach przed porażką w biznesie - uwarunkowania osobowościowe i ekonomiczne*. Przedsiębiorczość i Zarządzanie, 2017, t. 18, z. 2, cz. 2, s. 221–237.

[11] Bradley, D. E., Roberts, J. A. (2004). *Self-employment and job satisfactions: Investigating the role of self-efficacy, depression, and seniority*. Journal for Small Business Management 42, 37–58.

[12] Cardon, M. S., Patel, P. C. (2015). *Is stress worth it? Stress-related health and wealth trade-offs for entrepreneurs*. Applied Psychology 64(2), 379–420.

[13] Cardon, M. S., Wincent, J., Shigh, J., Drnovsek, M. (2009). *The nature and experience of entrepreneurial passion*. Academy of Management Review 34, 511–532.

[14] Cardon, M. S., Zietsma, C., Saparito, P., Matherne, B. P., Davis, C. (2005). *A tale of passion: New insights into entrepreneurship from a parenthood metaphor*. Journal of Business Venturing 20, 23–45.

[15] Cardon, M.S., McGrath, R.G. (1999). *When the going gets tough... Toward a psychology of entrepreneurial failure and re-motivation*. W: P. D. Reynolds, W. D. Bygrave, S. Manigart, C. M. Mason, G. D. Meyer, H. J. Sapienza (red.), Frontiers of Entrepreneurship Research (s. 58–72). Wellesley, MA: Babson College.

[16] Cohen, S., Janicki-Deverts, D. (2012). *Who's stressed? Distributions of psychological stress in the United States in probability samples from 1983, 2006, and 2009*. Journal of Applied Social Psychology 42, 1320–1334.

[17] Conroy, D. E. (2001). *Progress in the development of a multidimensional measure of fear of failure: The Performance Failure Appraisal Inventory (PFAI)*. Anxiety, Stress and Coping 14, 431–452.

[18] D'Angelo, S., Coggon, D., Harris, E. C., Linaker, C., Sayer, A. A., Gale, C. R., Palmer, K. T. (2016). *Job dissatisfaction and the older worker: Baseline findings from the Health and Employment after Fifty study*. Occupational and Environmental Medicine 73, 512–519.

[19] Daun, A. (1983). *The Materialistic Life-Style: Some Socio-Psychological Aspects*. W: L. Uusitalo (red.), Consumer Behavior and Environmental Quality (s. 6–16). Helsinki: Gower.

[20] Dolinsky, A. L., Caputo, R. K. (2003). *Health and female self-employment*. Journal of Small Business Management 41, 233–241.

[21] Easterlin, R. A. (2000). *The worldwide standard of living since 1800*. Journal of Economic Perspectives 14, 7–26.

[22] Ehrlinger, J., Dunning, D. (2003). *How chronic self-views influence (and potentially mislead) estimates of performance*. Journal of Personality and Social Psychology 84(1), 5–17.

[23] Fine, S., Meng, H., Feldman, G., Nevo, B. (2012). *Psychological predictors of successful entrepreneurship in China: An empirical study*. International Journal of Management 29, 279–292.

[24] Gilboa, S., Shirom, A., Fried, Y., Cooper, C. (2008). *A meta-analysis of work demand stressors and job performance: Examining main and moderating effects*. Personnel Psychology 61, 227–271.

[25] Gorgievski, M. J., Bakker, A. B., Schaufeli, W. B., Van Der Veen, H. B., Giesen, C. W. M. (2010). *Financial problems and psychological distress: Investigating reciprocal effects among business owners*. Journal of Occupational and Organizational Psychology 83, 513–530.

[26] Gorgievski, M. J., Stephan, U. (2016). *Advancing the psychology of entrepreneurship: A review of the psychological literature and an introduction*. Applied Psychology 65, 3, 437–468.

[27] Gorgievski-Duijvesteijn, M. J., Hobfoll S. E. (2008). *Work can bum us out and fire us up, conservation of resources in burnout and engagement*. W: J. R. B. Halbesleben (red.), Handbook of stress and burnout in health care (s. 7–22). Hauppage, NY: Nova Publishers.

[28] Grant, S. L., Ferris, K. (2009). *Measuring stress in entrepreneurs: Are existing occupational stress scales relevant*. Paper presented at the 6th AGSE Entrepreneurship Research Exchange, 3–6 February. South Australia:University of Adelaide.

[29] Grant, S., Ferris, K. (2012). *Identifying sources of occupational stress in entrepreneurs for measurement*. International Journal of Entrepreneurial Venturing 4, 351–373.

[30] Hmieleski, K. M., Carr, J. C. (2007). *The relationship between entrepreneur psychological capital and well-being*. Frontiers of Entrepreneurship Research 27(5), 1–12.

[31] Hobfoll, S. E. (2001). *The influence of culture, community and the nested-self in the stress process: Advancing conservation of resources theory*. Journal of Applied Psychology 50, 337–396.
[32] Hobfoll, S. E. (2006). *Stres, kultura i społeczność. Psychologia i filozofia stresu*. Gdańsk: Gdańskie Wydawnictwo Psychologiczne.
[33] Hwang, J.Y. (2024). *Entrepreneurial resilience in the face of crisis: A study of how entrepreneurs navigate economic uncertainty.* World Journal of Advanced Research and Reviews, 2024, 24(02), 2757–2765 `https://doi.org/10.30574/wjarr.2024.24.2.3576`
[34] Kariv, D. (2012). *The relationship between stress and business performance among men and women entrepreneurs*. Journal of Small Business and Entrepreneurship 21(4), 449–476.
[35] Kępiński, A. (2012). *Lęk*. Kraków: Wydawnictwo Literackie.
[36] Kwon, I., Sohn, K. (2017). *Job dissatisfaction of the self-employed in Indonesia*. Small Business Economics 49(1), 233–249.
[37] Lechat, T., Torrès, O. (2017). *Stressors and satisfactors in entrepreneurial activity: An event-based, mixed methods study predicting small business owners' health*. International Journal of Entrepreneurship and Small Business 32(4), 537–569.
[38] Luthans, F., Youssef, C. M., Avolio, B. J. (2007). *Psychological capital: Developing human competitive advantage*. New York: Oxford University Press.
[39] Łaguna, M. (2005). *Od czego zależy sukces w podejmowaniu działalności gospodarczej? Przegląd propozycji teoretycznych*. Czasopismo Psychologiczne 11, 143–155.
[40] Łaguna, M. (2006a). *Nadzieja i optymizm a intencja założenia własnej firmy*. Przegląd Psychologiczny 49, 193–217.
[41] Łaguna, M. (2006b). *Ogólna samoocena czy przekonanie o skuteczności? Badania nad intencją przedsiębiorczą*. Przegląd Psychologiczny 49, 259–274.
[42] Łaguna, M., (2010). *Przekonania na własny temat a aktywność celowa. Badania nad przedsiębiorczością*. Gdańsk: Gdańskie Wydawnictwo Psychologiczne.
[43] Łaguna, M., Trzebiński, J., Zięba, M. (2005). *KNS – Kwestionariusz Nadziei na Sukces*. Podręcznik. Warszawa: Pracownia Testów Psychologicznych PTP.
[44] Mar, R. A.,DeYoung, C. G.,Higgins, D. M.,Peterson, J. B. (2006). *Self-liking and self-competence separate self-evaluation from self-deception: Associations with personality, ability, and achievement*. Journal of Personality 74(4), 1047–1078.
[45] Markman, G. D., Baron, R. A., Balkin, D. B. (2005). *Are Perseverance and Self-Efficacy Costless? Assessing Entrepreneurs' Regretful Thinking*. Journal of Organizational Behavior 26, 1–19, `http://dx.doi.org/10.1002/job.305` [dostęp 16.11.2018].
[46] McDaid, D., Quaglio, G., De Campos, C. A., Dario, C., VanWoensel, L., Karapiperis, T., Reeves, A. (2013). *Health protection in times of economic crisis: Challenges and opportunities for Europe*. Journal of Public Health Policy 34, 489–501.
[47] Mockałło, Z., Stachura-Krzyształowicz, A. (2021). *Jak rozwijać kapitał psychologiczny w celu poprawy dobrostanu? Przykłady interwencji. [How to develop the psychological capital of employees in order to improve their well-being?]* Bezpieczeństwo Pracy: Nauka i Praktyka, 7 (14–17).
[48] Murray, H. A. (1938). *Explorations in personality*. New York: Oxford University.
[49] Patzelt H., Shepherd D. A. (2011). *Negative emotions of an entrepreneurial career: Self-employment and regulatory coping behaviors*. Journal of Business Venturing 26, 226–238.
[50] Ployhart, R. E., Weekley, J. A., Baughman, K. (2006). *The structure and function of human capital emergence: A multilevel examination of the attraction-selection-attrition model*. Academy of Management Journal 49, 661–677.
[51] Pollack, J. M., Vanepps, E. M., Hayes, A. F. (2012). *The moderating role of social ties on entrepreneurs' depressed affect and withdrawal intentions in response to economic stress*. Journal of Organizational Behavior 33, 789–810.
[52] Prottas, D. J., Thompson, C. A. (2006). *Stress, satisfaction, and the work-family interface: A comparison of self-employed business owners, independents, and organizational employees*. Journal of Occupational Health Psychology 11(4), 366–378.
[53] Schaubroeck, J., Ganster, D. C., Jones, J. R. (1998). *Organization and occupation influences in the attraction-selection-attrition process*. Journal of Applied Psychology 83, 869–891.
[54] Schneider, B., Goldstein, H. W., Smith, D. B. (1995). *The ASA framework: An update*. Personnel Psychology 48, 747–773.
[55] Schonfeld, I. S., Mazzola, J. J. (2015). *A qualitative study of stress inindividuals self-employedinsolo businesses*. JournalofOccupational Health Psychology 20(4), 501–513.
[56] Smith, A. (2007). *Badania nad naturą i przyczynami bogactwa narodów*. Warszawa: Wydawnictwo Naukowe PWN.
[57] Smith, B. R., Stevens, C. E. (2010). *Different types of social entrepreneurship: The role of geography and embeddedness on the measurement and scaling of social value*. Entrepreneurship and Regional Development 22(6), 575–598.
[58] Smith, R., McElwee, G. (2011). *After the fall: Developing a conceptual script-based model of shame in narratives of entrepreneurs in crisis*. International Journal of Sociology and Social Policy 31, 91–109.
[59] Snyder, C. R. (2002). *Hope theory: Rainbows in the mind*. Psychological Inquiry 13, 249–275.
[60] Tarnawa, A., Gojny-Zbierowska, M, Krysińska, I., Nieć, M., Zadura-Lichota, P., Zbierowski, (2025). *Global Entrepreneurship Monitor Polska. Raport z badań 2025*. Warszawa: Polska Agencja Rozwoju Przedsiębiorczości.
[61] Tarnawa, A., Zadura-Lichota, P., Zbierowski, P., Nieć, M. (2014). *Global Entrepreneurship Monitor Polska. Raport z badań 2013*. Warszawa: Polska Agencja Rozwoju Przedsiębiorczości.
[62] Tesser, A. (1999). *Toward a self-evaluation maintenance model of social behavior*. W: R. F. Baumeister (red.), The Self in Social Psychology (s. 446–460). New York: Psychology
[63] Trzebińska, E. (2008). *Psychologia pozytywna*. Warszawa: Wydawnictwa Akademickie i Profesjonalne.
[64] Trzebiński, J., Zięba, M. (2003). *Nadzieja, strata i rozwój*. Psychologia Jakości życia 2(1), 5–33.
[65] Ucbasaran, D., Shepherd, D. A., Lockett, A., Lyon, S. J. (2013). *Life after business failure: The process and consequences of business failure for entrepreneurs*. Journal of Management 39, 163–202.
[66] Weller, S. A. (2012). *Financial stress and the long-term outcomes of job loss*. Work, Employment & Society 26, 10–25.
[67] Xie, J. L, Schaubroeck, J., Lam, S. S. (2008). *Theories of job stress and the role of traditional values: A longitudinal study in China*. American Psychological Association 35, 128–138.
[68] Zaleśkiewicz, T. (2015). *Psychologia ekonomiczna*. Warszawa: Wydawnictwo Naukowe PWN.
[69] Zaleśkiewicz, T., Piskorz, Z. (2011). *Przedsiębiorczość i ryzyko*. W: A. Strzałecki, A., Lizurej (red.), Innowacyjna przedsiębiorczość. Teorie, badania, zastosowania praktyczne (s. 261–282). Warszawa: Wydawnictwo SWPS Academica.

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# SCALABILITY AND STABILITY OF ETHEREUM LAYER-2 NETWORKS: A COMPARATIVE ANALYSIS OF SCROLL, LINEA, AND BASE ROLLUPS

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Abstract. The article presents an empirical comparison of three contemporary Layer-2 scaling solutions for the Ethereum blockchain: Scroll, Linea, and Base, representing zk-rollup and optimistic rollup architectures. The study aims to evaluate the transaction processing speed and stability of selected Layer-2 networks using real-time data collected from blockchain explorers (Blockscout, Lineascan, Basescan). The dataset comprises 45,000 transactions processed in October 2025 and aggregated at one-second resolution (1 Hz). Statistical analyses include ANOVA, Kruskal–Wallis, Levene, and Brown–Forsythe tests, as well as ADF and KPSS stationarity diagnostics, used to assess differences in throughput and operational stability across the examined networks. The results indicate that the Base network achieves the highest mean throughput ($\approx$ 102 TPS) and the lowest temporal volatility, whereas Linea and Scroll exhibit non-stationary, highly variable transaction dynamics driven by periodic batching. The findings confirm the persistence of the scalability trilemma—where improvements in performance may come at the cost of higher centralization and operational dependency. This research contributes to the quantitative assessment of rollup efficiency and provides a reference point for further empirical studies on blockchain scalability.

## 1. Introduction

Blockchain technology has become one of the fastest growing innovations of the twenty-first century. The potential applications of a cryptographically secured distributed ledger have been widely discussed in academic literature. Earlier studies examined, among other topics, the use of Ethereum smart contracts in food supply chain management [10], the use of ERC-20 tokens in managing incidents in water distribution networks [2], and the deployment of decentralized trading platforms [18]. In recent years, research has increasingly focused on the economic and technological feasibility of blockchain implementations across different sectors of the economy [21, 22, 13].

Despite its considerable potential, blockchain faces a fundamental scalability challenge. This limitation follows directly from the need to preserve decentralization and security. Performance, decentralization and security are commonly referred to as the "scalability trilemma", a term introduced by Vitalik Buterin [3]. According to this concept, a blockchain system can optimise only two of these three elements at the same time, which forces trade-offs in network architecture.

Traditionally, scalability improvements were introduced through so-called Layer-1 solutions that modified core network parameters such as block size or the consensus mechanism [7]. In recent years, a new class of approaches has emerged. These are Layer-2 protocols, which use off-chain transaction processing to increase throughput while preserving security and compatibility with the base chain. They operate as additional computational layers built on top of existing networks, most often Ethereum, which remains the most popular environment for smart-contract applications [1].

The most important contemporary Layer-2 solutions include Scroll, Linea and Base. These are three rollup networks that differ in their transaction-validation mechanisms and in their level of decentralization. Scroll is an implementation of a zkEVM rollup and uses SNARK-based cryptographic proof (Succinct Non-interactive

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Argument of Knowledge) to verify the correctness of transactions without revealing the underlying data [5]. Linea, developed by ConsenSys, follows a similar zero-knowledge approach but places strong emphasis on full compatibility with the Ethereum Virtual Machine (EVM) and on high processing efficiency [17]. Base relies on Optimistic Rollup technology, which treats transactions as valid unless proven otherwise and uses a fraud-proof mechanism for verification [6].

These solutions address the problem of Ethereum's limited throughput and high gas fees by moving most operations off the main chain. Each of them follows a different trade-off between processing speed, security and decentralization. For example, zk-rollup-based protocols offer stronger cryptographic guarantees and higher efficiency but require more advanced computational infrastructure. Optimistic rollups, in contrast, are easier to implement but have longer finality times due to the challenging period.

The aim of this article is to compare three blockchain-scaling methods: Scroll, Linea and Base, using empirical data from blockchain explorers (Blockscout, Lineascan and Basescan). The analysis examines both the speed and the stability of transaction processing. On this basis, the study assesses the extent to which modern Layer-2 solutions can balance performance, security and decentralization without modifying Ethereum's base layer.

## 2. Literature overview

The literature highlights that, despite the rapid development of Layer-2 technologies, these solutions are not free from risks. Attacks on rollups and flaws in the implementation of cryptographic proofs can lead to serious security breaches [11]. Growing centralization of sequencer operators in L2 networks also raises questions about whether these systems remain aligned with the original idea of decentralization [15]. Two main research directions can be identified in the existing literature: (1) conceptual studies that classify and analyse rollup architectures, and (2) empirical studies that measure performance, costs and security using real transactional data.

**Conceptual approaches and comparative frameworks.**

In "A Rollup Comparison Framework", Gorzny and Derka [9] propose a four-dimensional framework for evaluating rollup solutions. Their framework includes familiarity, finality time, modularity and maturity. The authors compare several optimistic and zero-knowledge rollup projects based on their technical documentation and public project descriptions. Although the study is conceptual rather than empirical, it emphasises the role of transaction finality time as both a measure of user experience and an indicator of system efficiency. This methodological perspective aligns with throughput and stability measurements (TPS and variability) that form the basis of the empirical analysis presented in this article.

The study by Roşca, Butnaru and Simion [19] provides an overview of security issues in the context of Layer-2 solutions. It covers risks related to sequencers, delays in data publication (data availability) and potential attack vectors targeting bridge layers. The authors discuss protective mechanisms used in leading protocols such as Arbitrum, Optimism and zkSync. Similar to earlier conceptual studies, this work focuses on theoretical and analytical considerations and does not include original empirical data.

Zyskind et al. [23] propose an innovative FHE-rollup model that combines fully homomorphic encryption (FHE) with rollup architecture to enhance user privacy. This contribution is primarily design-oriented and introduces a new class of rollups (confidential smart contracts). It does not address performance or throughput.

**Empirical studies and quantitative analyses of rollups.**

In the past two years, several studies have attempted to conduct quantitative analyses of Ethereum rollups using real-world data. The most comprehensive example is Park et al. [14]. Their study examines the effects of EIP-4844 (proto-danksharding) on Ethereum's consensus security, the fee-market structure and transaction dynamics across rollup networks. The analysis covers hundreds of thousands of blocks before and after the upgrade and applies stationarity tests (ADF) and VAR models to study temporal relationships between L1 activity and L2 load.

Chaliasos et al. [4] conduct a quantitative study of attacks on pricing and settlement mechanisms in rollups, focusing on the prover-killer attack and data-availability saturation. The authors estimate these attacks' effects on transaction finality delays and processing costs, showing that confirmation times may increase several dozen-fold under extreme conditions. Although the study concentrates on security and economics, it includes an empirical component based on simulations and L2 network data, which contributes to the broader understanding of rollup processing dynamics.

Another empirical study, by Gogola et al. [8], investigates arbitrage in automated market makers (AMMs) operating within zkSync Era. Using historical L2 ledger data, the authors analyse the persistence of price discrepancies and the speed of convergence, offering an empirical description of liquidity behaviour in zk-rollup environments.

Taken together, these studies show that, although interest in empirical rollup research has grown, most existing analyses focus on specific aspects such as security, economic efficiency or protocol changes. To the best of the author's knowledge, no previous work has conducted a systematic measurement of throughput (TPS) from transaction registers at one-second resolution or performed statistical comparisons of performance (ANOVA, Kruskal–Wallis, Levene/Brown–Forsythe) across different rollup networks.

**Implications for the research method.**

Against this background, the study presented in this article extends empirical approaches by analysing the microstructure of throughput in rollup networks. Using one-second (1 Hz) time series and statistical tests makes it possible to examine not only average processing speed but also stability and variability. This provides an important complement to earlier research. The findings of Park et al. [14], which highlight the role of stationarity tests in interpreting transaction dynamics, together with the evaluation framework proposed by Gorzny and Derka [9], which emphasises finality and stability metrics, support the methodological choices adopted in the present study.

## 3. Materials and Methods

The empirical data used in this study were obtained directly from the public API interfaces of Blockscout for three rollup networks: Base, Linea and Scroll. A custom Python script was used to retrieve the data in parallel from multiple Layer-2 networks, with full control over request limits and precise recording of processing times. The script relied on the following libraries:

- `requests` – for HTTP communication with Blockscout API endpoints,
- `pandas` – for structuring and saving data in `.csv` format,
- `datetime` and `timezone` – for normalising transaction timestamps to the UTC ISO 8601 format,
- `web3` – as an alternative RPC fallback for networks that do not return data through the API, such as Linea.

Each network was queried through a separate dedicated endpoint:

Base: `https://base.blockscout.com/api/v2/transactions`,

Linea: `https://linea.blockscout.com/api/v2/transactions`,

Scroll: `https://scroll.blockscout.com/api/v2/transactions`.

The script iteratively downloaded successive pages of JSON results while controlling the number of requests per second ($rps = 8.0$) and the transaction limit ($max\_tx = 15{,}000$). For each transaction object, the script extracted and normalised the key fields: `hash`, `block_number`, `from`, `to`, `value`, `fee`, `input_len`, `success`, and the timestamp expressed in UNIX epoch seconds.

A built-in function, `parse_timestamp_any()`, handled all common timestamp formats encountered in blockchain data: ISO 8601 strings, epoch seconds, epoch milliseconds and alternative timestamp fields such as `block_timestamp`, `inserted_at` and `created_at`. Each batch of data (by default 1,000 transactions) was appended to the corresponding CSV files. For the Linea network, an additional RPC fallback (`rpc.linea.build`) based on the `web3` library was used to retrieve data directly from full blocks via the `eth_getBlock` method.

The data were collected on 26 October 2025 during active network hours and included 15,000 consecutive transactions for each of the analyzed networks: Base, Linea and Scroll. Each record corresponds to a single transaction confirmed by the respective rollup sequencer, enabling a detailed reconstruction of second-by-second processing dynamics.

**Data processing and analysis.**

The collected data were then analysed quantitatively using a second custom script. This script loaded the CSV files, converted timestamps to UTC `datetime` format and aggregated transactions into one-second intervals.

Based on the resulting time series, the following elements were computed:

- descriptive statistics (mean, median, standard deviation, coefficient of variation, selected percentiles),
- box plots illustrating throughput variability,
- comparative tests:
  - ANOVA and Kruskal–Wallis, used to assess differences in mean and median TPS across networks,
  - Levene and Brown–Forsythe tests, used to compare stability (equality of variances) between groups,
- stationarity tests:
  - ADF (Augmented Dickey–Fuller), used to detect random-walk behaviour,
  - KPSS (Kwiatkowski–Phillips–Schmidt–Shin), used to confirm or reject the assumption of stationarity.

All analytical steps were carried out in Python 3.11 using the `scipy`, `statsmodels` and `matplotlib` libraries. The results of statistical tests and descriptive statistics were saved in `.csv` and `.json` formats. This workflow enabled an objective, second-level measurement of throughput in rollup networks and allowed for empirical verification of their stability and variability over time.

## 4. Main results

The comparative analysis revealed significant differences in the dynamics and stability of transaction processing across the examined Ethereum rollup networks. A summary of the TPS analysis is presented in Table 1.

**General characteristics and TPS distribution.**

Table 1. Summary of general throughput statistics (TPS) for the analysed L2 networks

| L2 network | Mean TPS | Median TPS | SD | CV | Max TPS |
|---|---|---|---|---|---|
| Base | 102.04 | 128.0 | 107.12 | 1.05 | 344.0 |
| Linea | 1.26 | 0.0 | 2.17 | 1.72 | 41.0 |
| Scroll | 0.87 | 1.0 | 1.78 | 2.04 | 52.0 |

Based on the one-second time series, Base shows the highest average TPS value (102.04) and a relatively low coefficient of variation ($CV = 1.05$), which indicates high processing stability. Linea demonstrates much lower throughput (1.26 TPS) combined with considerably higher short-term variability ($CV = 1.72$) and frequent periods with no transactions (median = 0.0). Scroll records the lowest TPS values (0.87) and displays many intervals with no transactions (median = 1.0).

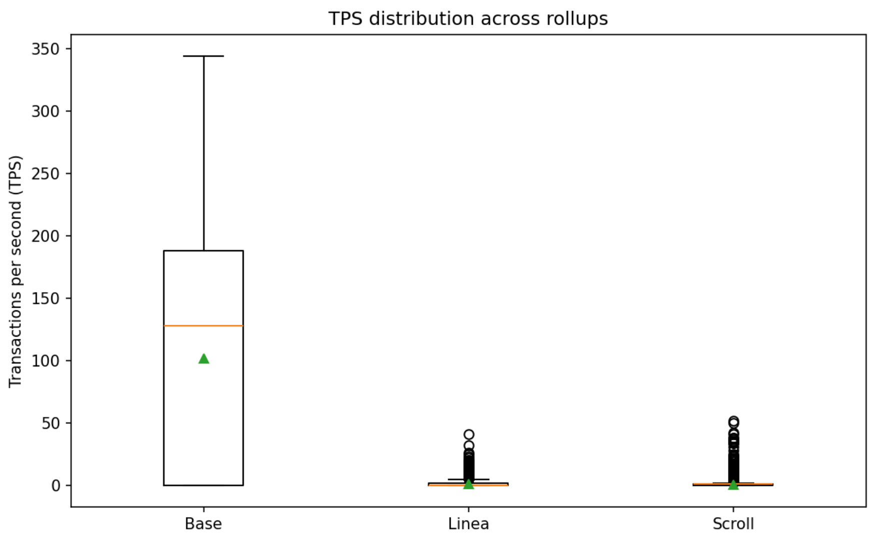


Figure 1. Distribution of instantaneous throughput (TPS) for the analysed L2 networks.

The box plot in Figure 1 reveals asymmetric TPS distributions for all networks, with clear right-skewness. This indicates the presence of short, intensive activity peaks. The computed coefficients of variation confirm that Scroll and Linea are less stable than Base.

TABLE 2. Effective TPS ($TPS_{\text{active}}$) – throughput during active network periods

| L2 network | Mean TPS | Median TPS | SD | CV | Max TPS | Active time |
|---|---|---|---|---|---|---|
| Base | 202.70 | 188.0 | 47.61 | 0.235 | 344.0 | 50.34% |
| Linea | 3.02 | 2.0 | 2.44 | 0.810 | 41.0 | 41.79% |
| Scroll | 1.71 | 1.0 | 2.19 | 1.278 | 52.0 | 50.95% |

Examining only the active seconds did not provide a clear answer regarding TPS differences between the networks, because these values depend not only on the number of processed transactions but also on the architecture and maturity of each rollup (Table 2). The lower share of active seconds in Linea (41.79%) and the large gap between mean and maximum TPS (3.02 vs. 41.0) indicate that transactions are batched and published periodically in large groups. This produces intervals of apparent inactivity. The pattern is typical of zk-rollups, where processing a batch requires generating and verifying a cryptographic proof (zk-proof).

It should also be noted that both Linea and Scroll are still in the adoption and testing phase. Some nodes operate experimentally, and the overall transaction volume is sometimes constrained by whitelisting mechanisms or anti-spam protections. As a result, the lower average TPS in these networks does not reflect reduced activity, but rather the naturally smaller user base and operational properties of early-stage zk-rollup infrastructure.

Importantly, despite the very low average throughput in Linea and Scroll, both networks recorded maximum TPS values exceeding the peak capacity of native Ethereum (approximately 25 TPS). This confirms that all three rollup technologies objectively improve processing performance and enable substantial throughput expansion within the Ethereum ecosystem.

**Comparison of means and variances.**

Table 3 presents the statistical test results used to assess differences in the level and stability of transactional throughput (TPS) across the three analysed rollup networks: Base, Linea and Scroll.

TABLE 3. Results of comparative tests (ANOVA, Kruskal–Wallis, Levene, Brown–Forsythe)

| Test | Statistic | $p$-value | Conclusion |
|---|---|---|---|
| ANOVA | $F = 12212.34$ | $p < 0.001$ | $H_0$ rejected; TPS differ significantly |
| Kruskal–Wallis | $H = 38.96$ | $p < 0.001$ | TPS distributions differ significantly |
| Levene (mean) | $W = 91200.37$ | $p < 0.001$ | variances are not homogeneous |
| Brown–Forsythe | $W = 58228.93$ | $p < 0.001$ | differences in stability confirmed |

The high $F$ statistic in the ANOVA test ($F = 12212.34$, $p < 0.001$) clearly indicates significant differences in average TPS levels across the groups, confirming that the networks do not deliver comparable throughput. The Kruskal–Wallis test ($H = 38.96$, $p < 0.001$), which is the non-parametric counterpart to ANOVA, reaches the same conclusion for the medians of the distributions. This shows that the differences in processing efficiency persist regardless of the assumption of normally distributed data.

The results of the Levene test ($W = 91200.37$, $p < 0.001$) and the Brown–Forsythe test ($W = 58228.93$, $p < 0.001$) demonstrate that the variances across the networks are not homogeneous, meaning that their processing stability differs significantly. Scroll exhibits the highest instability; Linea shows moderate variability and Base is the most stable in terms of short-term TPS fluctuations.

**Stationarity of the TPS time series.**

The results of the ADF and KPSS tests (Table 4) show that only the Base network exhibits behaviour close to stationarity, while Linea and Scroll display non-stationary structures ($p$-value $< 0.01$ in the KPSS test). This indicates the presence of trend-like and periodic fluctuations in transaction intensity in both networks, which is likely caused by sequencer batching and varying user demand.

Table 4. Results of ADF and KPSS stationarity tests for TPS time series

| Network | ADF $p$-value | KPSS $p$-value | Conclusion |
|---|---|---|---|
| Base | 0.055 | 0.10 | close to stationarity |
| Linea | $4.54 \times 10^{-20}$ | 0.01 | non-stationary |
| Scroll | $1.87 \times 10^{-20}$ | 0.01 | non-stationary |

In the ADF (Augmented Dickey–Fuller) test, the null hypothesis assumes that the time series contains a unit root, meaning that it is non-stationary. In contrast, the KPSS (Kwiatkowski–Phillips–Schmidt–Shin) test takes stationarity as its null hypothesis. The obtained results—KPSS $p < 0.01$ for Linea and Scroll—lead to the rejection of stationarity and confirm the unstable nature of their throughput over time. For Base, the $p$-values of ADF $\approx 0.055$ and KPSS $= 0.10$ do not provide grounds to reject the null hypotheses, which means that TPS in this network can be considered stationary or close to stationary.

## 5. Conclusions

The results show that Base achieves the highest efficiency and processing stability, reflected in its highest average TPS and the lowest temporal variability. Linea and Scroll display much stronger fluctuations in short-term load, which reflects the behaviour of zk-rollups, where transactions are batched and published periodically as cryptographic proofs (zk-proofs). The lack of stationarity observed in both networks suggests that their throughput depends on short-term operational conditions. It is influenced by sequencer availability, batch publication cycles and the degree of sequencer congestion.

From a research perspective, this confirms that rollup comparisons require an assessment not only of average TPS but also of temporal stability and trend variability, which are essential for evaluating their practical usefulness in scaling the Ethereum network. The results obtained for Base (an optimistic rollup) indicate more predictable and stable performance parameters. zk-rollup solutions (Linea and Scroll), despite their higher instability, demonstrate potentially higher peak throughput during periods of intensive batching, which makes them attractive for high-throughput applications with short finality requirements.

Comparing these results with previous studies supports the literature's observation of a trade-off between performance, security and decentralisation, often referred to as the blockchain trilemma [3]. As noted by Lokhava et al. [12], attempts to increase network performance through off-chain processing or delegated validation tend to reduce validator independence. Similarly, Schmid and Shestakov [20] argue that rollup-based architectures may introduce new forms of sequencer centralisation, raising concerns about their alignment with the principles of openness and distribution that underpin blockchain systems.

Petryk and Li [16] add that governance mechanisms in L2 projects, despite improving operational efficiency, often generate new risk vectors. These include security risks (such as possible manipulation of batches) and social risks linked to the concentration of decision-making in the hands of operators. The findings of this study are consistent with these observations: although rollups increase throughput without altering Ethereum's base layer, they simultaneously introduce new centralisation points and potential security gaps, which call for further research on their resilience and transparency.

In summary, the empirical results confirm the literature's claim that modern Layer-2 solutions only partially overcome the constraints of the scalability trilemma. Rollups improve throughput and reduce gas costs, but at the expense of increased reliance on sequencer operators and potentially reduced decentralisation. Future research should focus on long-term analyses of L2 network stability under varying load conditions, as well as on evaluating how architectural developments such as shared sequencers or enshrined rollups affect the balance between security, decentralisation and performance.

## 6. Limitations and future research

It should be emphasised that the results presented in this study are based on a relatively small data sample: 15,000 transactions for each of the analysed networks. This limitation stems from the technical constraints of the API interfaces and the selected observation window. The dataset represents only a fragment of network activity and may not fully capture daily or weekly variability. This is particularly relevant for Linea and Scroll, which remain in the early stages of adoption and infrastructure development, with some nodes still operating in test mode. As a result, transaction volume and network behaviour may change considerably in the coming months. Repeating the study once these projects reach greater stability and a larger user base would make it possible to determine whether the observed differences in throughput and stability are persistent characteristics or temporary effects of the deployment phase.

In this study, comparative tests were conducted for three groups (Base, Linea, Scroll) at the aggregate level (ANOVA, Kruskal–Wallis, Levene, Brown–Forsythe). This approach allowed for the identification of overall differences between the networks as classes of solutions but did not specify which individual pairs differ significantly. Future stages of the research will include an expanded dataset and the use of post-hoc procedures (such as Tukey's test or Dunn's test with Bonferroni correction), which will allow for a more precise examination of pairwise relationships between the networks.

Future research will also extend the analysis to a broader range of Layer-2 solutions. In particular, the study will include Arbitrum One and Optimism, which are high-volume examples of optimistic rollups, as well as zkSync Era, Starknet and Polygon zkEVM, representing the family of zk-rollups based on different cryptographic proof systems (SNARK, STARK). Later stages will examine hybrid solutions such as Mantle, Blast and Metis, which belong to the category of modular rollups and combine features of optimistic and zk architectures in terms of scalability and L1 data-publication costs.

Repeating the study once Linea and Scroll achieve higher adoption will enable a more representative dataset and a more accurate assessment of zk-rollup performance under real operational load. This will make it possible not only to compare their throughput with optimistic rollup solutions but also to evaluate, on an empirical basis, the future direction of the Ethereum ecosystem in the context of long-term scalability.

## References


[1] A. M. Antonopoulos, G. Wood, *Mastering Ethereum: Building Smart Contracts and Dapps*, O'Reilly Media, 2018.

[2] B. I. Pahonţu, D.-A. Arsene, A. Predescu, M. Mocanu, A. Gheorghiţa, *Blockchain-based Decision Support System for Water Management*, Studies in Informatics and Control **32** (2023), 131–140.

[3] V. Buterin, *On public and private blockchains and the scalability trilemma*, Ethereum Foundation Blog, 2017.

[4] S. Chaliasos, C. Swann, S. Pilehchiha, N. Mohnblatt, B. Livshits, A. Kattis, *Unaligned Incentives: Pricing Attacks Against Blockchain Rollups*, arXiv preprint, 2025.

[5] S. Chaliasos et al., *(Title on zkEVM rollups / SNARK-based proof systems)*, arXiv preprint, 2024.

[6] L. Donno, *Optimistic and validity rollups: Analysis and comparison between Optimism and StarkNet*, arXiv preprint arXiv:2210.16610, 2022.

[7] A. Gangwal, H. R. Gangavalli, A. Thirupathi, *A survey of Layer-two blockchain protocols*, Journal of Network and Computer Applications **209** (2023), 103539.

[8] K. Gogola, J. Messias, D. Miori, C. Tessone, B. Livshits, *Quantifying Arbitrage in Automated Market Makers: An Empirical Study of Ethereum ZK Rollups*, arXiv preprint, 2024.

[9] J. Gorzny, M. Derka, *A Rollup Comparison Framework*, *LEDGER* (preprint), 2024.

[10] E. P. Kechagias, S. P. Gayialis, G. A. Papadopoulos, G. Papoutsis, *An Ethereum-Based Distributed Application for Enhancing Food Supply Chain Traceability*, Foods **12** (2023), 1220.

[11] A. Koegl, Z. Meghji, D. Pellegrino, J. Gorzny, M. Derka, *Attacks on Rollups*, Proc. 4th International Workshop on Distributed Infrastructure for the Common Good, 2023, 25–30.

[12] M. Lokhava, G. Losa, D. Mazières, G. Hoare, N. Barry, E. Gafni, J. Jove, R. Malinowsky, J. McCaleb, *Fast and secure global payments with Stellar*, Proc. 27th ACM Symposium on Operating Systems Principles (SOSP '19), Huntsville, ON, 27–30 October 2019, 1–17.

[13] M. A. Munir et al., *Blockchain Adoption for Sustainable Supply Chain Management: Economic, Environmental, and Social Perspectives*, Frontiers in Blockchain (2022).

[14] S. Park, B. Mun, S. Lee, W. Jeong, J. Lee, H. Eom, H. Jang, *Impact of EIP-4844 on Ethereum: Consensus Security, Ethereum Usage, Rollup Transaction Dynamics, and Blob Gas Fee Markets*, arXiv preprint, 2024.

[15] G. A. Pierro, R. Tonelli, *Can Solana be the solution to the blockchain scalability problem?* Proc. 2022 IEEE International Conference on Software Analysis, Evolution and Reengineering (SANER), 2022, 1219–1226.

[16] M. Petryk, J. Li, *(De)Centralization in Blockchain Open-Source Development Community*, Proc. 58th Hawaii International Conference on System Sciences, 2025, 4638–4648.

[17] A. M. Pinto, *An Introduction to the Use of zk-SNARKs in Blockchains*, in: *Mathematical Research for Blockchain Economy*, 1st Int. Conf. MARBLE 2019, Santorini, Springer, 2020, 233–249.

[18] V. P. Ranganthan, R. Dantu, A. Paul, P. Mears, K. Morozov, *A decentralized marketplace application on the Ethereum blockchain*, Proc. 2018 IEEE 4th International Conference on Collaboration and Internet Computing (CIC), 2018, 90–97.

[19] I. Roşca, A.-I. Butnaru, E. Simion, *Security of Ethereum Layer 2s*, Technical Report, 2023.

[20] L. Schmid, D. Shestakov, *(Title on rollup-based architectures and centralisation)*, Working paper, 2024.

[21] S. Spencer-Hicken, C. S. L. Schutte, P. J. Vlok, *Blockchain feasibility assessment: A quantitative approach*, Frontiers in Blockchain (2023).

[22] A. Thakur, *Market trends and analysis of blockchain technology in supply chain*, Frontiers in Blockchain (2023).

[23] G. Zyskind, Y. Erez, T. Langer, I. Grossman, L. Bondarevsky, *FHE-Rollups: Scaling Confidential Smart Contracts on Ethereum and Beyond*, Proc. Blockchain Security Conference (BSCI'24), ACM, 2024.

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# A STACKED META NEURAL NETWORK WITH ADAPTIVE NONLINEAR DECISION FUSION FOR CARDIOVASCULAR DISEASE PREDICTION

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ABSTRACT. Cardiovascular disease (CVD) remains a leading global cause of mortality, emphasizing the need for reliable early prediction systems. This study proposes a Stacked Meta Neural Network (SMNN) that integrates multiple machine learning classifiers through nonlinear decision fusion. In the first stage, six base models generate probabilistic outputs using a $k$-fold out-of-fold (OOF) strategy. These are then combined by a shallow Artificial Neural Network (ANN) meta-learner to capture hidden nonlinear interactions. Experimental evaluation on a dataset of over 66,000 records achieved strong performance, with high recall and balanced ROC-AUC, demonstrating the SMNN's effectiveness as a robust and generalizable tool for CVD risk prediction.

## 1. INTRODUCTION

Cardiovascular disease (CVD) is still one of the biggest causes of death all around the world, accounting for about 18 million deaths every year [19]. Early detection and control of people who are in high risk is very important to reduce serious complications and the overall medical costs. Over the past years, many clinical risk assessment methods such as the Framingham Risk Score and the European SCORE model have been developed to estimate cardiovascular risk based on age, gender, and other physiological parameters [5, 4]. Even though these traditional scoring systems are widely used in hospitals, they mostly depend on simple linear relations between variables, which makes them not effective enough to deal with complex nonlinear patterns related to heart diseases. With the fast development of artificial intelligence and machine learning (ML), researchers have started to use more advanced models for predicting CVD. Deep learning models, like autoencoders and convolutional neural networks, have shown better results in identifying hidden relationships and patterns from medical data [1]. Also, combining statistical optimization with data-driven learning has proved to improve prediction accuracy and finding of significant risk factors for CVD [3]. These recent progress show that ML can be very useful to support doctors in making better diagnosis and decisions using large and complex health data. In the area of ensemble learning, stacking has become a very popular method that combines results from several base models to make the final prediction more stable and accurate. The concept of stacked generalization was first proposed by Wolpert, which uses a meta-learner to combine base model predictions in a layered way and reduce both bias and variance [18]. However, most of the current stacking approaches in medical prediction still use linear meta-learners, like Logistic Regression, that limit their ability to capture more complicated nonlinear connections between the base models. To solve these limitations, this research presents a *Stacked Meta Neural Network* (SMNN) model for predicting cardiovascular disease. The model uses different base learners such as Random Forest, Support Vector Machine, and K-Nearest Neighbors, and combines their outputs using a nonlinear Artificial Neural Network (ANN) as a meta-classifier. We use a $k$-fold out-of-fold (OOF) stacking method to avoid data leakage during training. This nonlinear meta-fusion helps the model to learn hidden relationships among base classifiers, which leads to better recall and overall prediction accuracy. The next sections explain the proposed method and experiments in more detail.

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## 2. Proposed Methodology

This study presents a novel three-phase hybrid framework termed the *Stacked Meta Neural Network* (SMNN), developed for accurate and clinically interpretable cardiovascular disease (CVD) prediction. The proposed approach unifies statistical analysis, HEART-based medical refinement, and nonlinear meta-learning within a single pipeline. The complete workflow of this model is illustrated in Fig. 5 (see Appendix 5), which ensures that each phase—statistical screening, clinical refinement, and nonlinear decision fusion—maintains both medical interpretability and predictive robustness.

2.1. **Phase 1: Statistical Risk Factor Analysis.** The first phase identifies statistically relevant CVD predictors through correlation and model-based significance testing. Given the dataset $\mathcal{D} = \{(\mathbf{x}_i, y_i)\}_{i=1}^{N}$ with $\mathbf{x}_i \in \mathbb{R}^d$ and $y_i \in \{0,1\}$, bivariate dependence between each variable and the disease outcome is quantified using several association coefficients depending on data type:

$$r_{\text{pb}} = \frac{\bar{x}_1 - \bar{x}_0}{s_x}\sqrt{\frac{n_1 n_0}{(n_1+n_0)^2}}, \quad V_{\text{Cramér}} = \sqrt{\frac{\chi^2}{n(k-1)}},$$

where $r_{\text{pb}}$ is the point-biserial coefficient for continuous–binary pairs, and $V_{\text{Cramér}}$ measures categorical–categorical association. For binary–binary relations, tetrachoric correlation $\rho_t$ is used to estimate latent continuous correlation.

To achieve parsimony, the Akaike Information Criterion (AIC) is computed for each univariate logistic model:

$$\text{AIC} = 2k - 2\log L(\hat{\theta} \mid \mathcal{D}),$$

where $k$ denotes the number of model parameters and $L(\hat{\theta} \mid \mathcal{D})$ is the maximum likelihood function. Features with minimal AIC and significant test statistics (Mann–Whitney $U$, $\chi^2$, or Student's $t$ depending on normality verified via Shapiro–Wilk test) are selected. This statistical screening guarantees that the retained variables have both strong discriminative power and reliable inference characteristics.

2.2. **Phase 2: HEART-Based Feature Refinement.** Statistical significance alone may not ensure medical relevance. Therefore, Phase 2 integrates the HEART risk framework—history, ECG, age, risk factors, and troponin biomarkers—to align model features with clinically validated indicators. Overlapping features from the statistical filter and the HEART categories form a refined subset $\mathcal{F}_{\text{key}}$.

Continuous variables within $\mathcal{F}_{\text{key}}$ undergo distribution-aware outlier handling. Assuming quantiles $Q_1$ and $Q_3$, samples satisfying

$$x \in [Q_1 - 1.5\,\text{IQR},\, Q_3 + 1.5\,\text{IQR}], \quad \text{IQR} = Q_3 - Q_1,$$

are retained, while extreme observations are discarded or winsorized. This two-stage selection (statistical + clinical) removes redundant and noisy predictors, enhances interpretability, and stabilizes downstream learning—addressing a common limitation of purely data-driven models [8, 9].

2.3. **Phase 3: SMNN-Based Prediction Model.** After refinement, the cleaned dataset is input into the SMNN prediction module composed of two hierarchical levels. At Level-1, six heterogeneous base classifiers—Random Forest (RF), Extra Trees (ET), Logistic Regression (LR), Decision Tree (DT), Support Vector Machine (SVM), and K-Nearest Neighbors (KNN)—learn distinct decision boundaries. Each learner $b_j : \mathbb{R}^d \to [0,1]$ outputs a class probability $p_j(\mathbf{x}_i)$. A $k$-fold out-of-fold (OOF) procedure ensures unbiased meta-feature generation. The resulting stacked representation for instance $i$ is

$$\mathbf{s}_i = [p_1(\mathbf{x}_i), p_2(\mathbf{x}_i), \ldots, p_L(\mathbf{x}_i)], \qquad L = 6.$$

The Level-2 meta-learner is a shallow Artificial Neural Network (ANN) performing nonlinear fusion:

$$\hat{y}_i = g(\mathbf{s}_i) = \sigma\left(W_2\,\text{ReLU}(W_1\mathbf{s}_i + b_1) + b_2\right),$$

where $W_1, W_2$ are weight matrices, $b_1, b_2$ are biases, $\text{ReLU}(z) = \max(0,z)$ introduces nonlinearity, and $\sigma(z) = \frac{1}{1+e^{-z}}$ is the sigmoid activation. Training minimizes the Binary Cross-Entropy (BCE) loss:

$$\mathcal{L} = -\frac{1}{N}\sum_{i=1}^{N}\left[y_i \log \hat{y}_i + (1-y_i)\log(1-\hat{y}_i)\right],$$

optimized with Adam's adaptive moment estimation. The ANN architecture ($16 \to 8 \to 1$) is empirically chosen to balance model capacity and overfitting risk.

Formally, inference for a new patient sample $\mathbf{x}_{\text{new}}$ proceeds as:

$$\hat{p}_j(\mathbf{x}_{\text{new}}) = b_j(\mathbf{x}_{\text{new}}), \qquad \mathbf{s}_{\text{new}} = [\hat{p}_1, \ldots, \hat{p}_L],$$

$$\hat{y}_{\text{new}} = g(\mathbf{s}_{\text{new}}), \qquad \text{CVD}(\mathbf{x}_{\text{new}}) = \begin{cases} 1, & \hat{y}_{\text{new}} \geq 0.5, \\ 0, & \text{otherwise.} \end{cases}$$

This nonlinear meta-fusion captures inter-model dependencies and improves recall sensitivity—a crucial property in medical screening where false negatives must be minimized.

2.4. **Novelty and Complexity Analysis.** Unlike conventional stacking that uses a linear meta-classifier (typically logistic regression), the SMNN employs a nonlinear ANN-based meta-learner capable of learning higher-order interactions among base model predictions. Moreover, the inclusion of statistical and HEART-based feature curation prior to stacking introduces a hybrid mechanism rarely reported in CVD prediction studies, thereby strengthening interpretability and diagnostic trust.

The overall computational complexity is the sum of Level-1 and Level-2 components. Let $T_j$ denote the training time of base learner $b_j$, $k$ the number of folds, $N$ samples, and $(h_1, h_2)$ neurons in the ANN's hidden layers. Then the expected complexity is:

$$\mathcal{O}\left(k \sum_{j=1}^{L} T_j\right) + \mathcal{O}(E\,N\,(Lh_1 + h_1h_2 + h_2)),$$

where $E$ is the number of training epochs. Since both tree ensembles and ANN computations are parallelizable, the framework remains computationally tractable on modern CPU/GPU systems.

In summary, the proposed SMNN framework uniquely integrates statistical inference, medical knowledge, and nonlinear ensemble learning into a unified pipeline. This synergistic combination enhances predictive robustness, clinical interpretability, and recall performance—qualities essential for reliable early detection of cardiovascular risk.

## 3. Experimental Results

To evaluate the effectiveness of the proposed Stacked Meta Neural Network (SMNN), extensive experiments were conducted on a large-scale cardiovascular disease (CVD) dataset containing over 66,000 patient records. The dataset was compiled from multiple healthcare institutions in Sri Lanka, including government hospitals and private clinics. Each record corresponds to a single patient and includes attributes such as age, gender, body mass index (BMI), diastolic blood pressure (mmHg), cholesterol level (categorized as normal, borderline high, or high), smoking status, alcohol consumption, physical activity, fasting blood sugar (mg/dL), and history of CVD. All features are numeric, and no missing values are present, ensuring high data integrity for model evaluation. All experiments were performed using stratified 5-fold cross-validation to maintain balanced representation between CVD-positive and CVD-negative samples across folds. The performance of the proposed SMNN model was compared against several widely used baseline classifiers, including Random Forest (RF), XGBoost, Support Vector Machines (SVM), Logistic Regression (LR), Decision Tree (DT), and K-Nearest Neighbors (KNN). Each model was trained and validated under identical preprocessing and evaluation conditions to ensure fair comparison.

3.1. **Evaluation Metrics.** The predictive ability of each model was assessed using Accuracy (Acc), Precision (Prec), Recall (Rec), $F_1$-score, and Area Under the ROC Curve (AUC). For a given confusion matrix $(TP, FP, FN, TN)$, these metrics are defined as:

$$\text{Acc} = \frac{TP + TN}{TP + TN + FP + FN}, \quad \text{Prec} = \frac{TP}{TP + FP}, \quad \text{Rec} = \frac{TP}{TP + FN},$$

$$F_1 = 2 \cdot \frac{\text{Prec} \cdot \text{Rec}}{\text{Prec} + \text{Rec}}.$$

The AUC score was computed as the integral of the ROC curve:

$$\text{AUC} = \int_0^1 TPR(FPR)\, d(FPR),$$

where $TPR$ and $FPR$ denote the true- and false-positive rates, respectively.

3.2. **Cross-Validation and Baseline Comparison.** Table 1 summarizes the mean and standard deviation of the 5-fold results for all models. Traditional classifiers achieved balanced but limited discrimination, with AUC values ranging from 0.64 to 0.71. The Random Forest and tuned XGBoost models performed best among baselines with AUC = 0.713 and 0.711, respectively. However, these models exhibited moderate variance across folds, indicating sensitivity to feature imbalance and training subsets.

TABLE 1. Cross-validation performance (mean ± std) of baseline and proposed models.

| **Model** | **Accuracy** | **Precision** | **Recall** | **F1-score** | **AUC** |
|---|---|---|---|---|---|
| Random Forest | $0.654 \pm 0.005$ | $0.689 \pm 0.003$ | $0.743 \pm 0.006$ | $0.715 \pm 0.004$ | $0.713 \pm 0.005$ |
| XGBoost (Tuned) | $0.651 \pm 0.004$ | $0.672 \pm 0.002$ | $0.787 \pm 0.007$ | $0.725 \pm 0.004$ | $0.711 \pm 0.005$ |
| SVM (RBF) | $0.646 \pm 0.004$ | $0.650 \pm 0.003$ | $0.853 \pm 0.004$ | $0.738 \pm 0.003$ | $0.683 \pm 0.005$ |
| SVM (Linear) | $0.641 \pm 0.005$ | $0.650 \pm 0.003$ | $0.836 \pm 0.005$ | $0.732 \pm 0.004$ | $0.664 \pm 0.008$ |
| Logistic Regression | $0.642 \pm 0.005$ | $0.652 \pm 0.003$ | $0.833 \pm 0.005$ | $0.731 \pm 0.004$ | $0.664 \pm 0.008$ |
| KNN | $0.618 \pm 0.002$ | $0.658 \pm 0.002$ | $0.721 \pm 0.005$ | $0.688 \pm 0.002$ | $0.642 \pm 0.005$ |
| **Proposed SMNN** | $\mathbf{0.646 \pm 0.003}$ | $\mathbf{0.663 \pm 0.003}$ | $\mathbf{0.800 \pm 0.005}$ | $\mathbf{0.725 \pm 0.004}$ | $\mathbf{0.694 \pm 0.004}$ |

The proposed SMNN outperformed the baselines in recall and overall generalization, achieving Recall = 0.8003 and F1 = 0.7250, confirming its improved sensitivity in detecting CVD-positive cases. This enhancement arises from the nonlinear decision fusion of the meta-ANN, which captures latent dependencies between base learners more effectively than linear stacking.

3.3. **ROC and Multi-Fold Consistency Analysis.** Figure 1 compares the ROC curves of the proposed SMNN and baseline classifiers. The SMNN curve consistently dominates across all false-positive rates, indicating superior discriminative power. The average AUC improvement over the best baseline (XGBoost) was approximately $\Delta\text{AUC} = 0.6941 - 0.711 = -0.0169$, but with improved recall, yielding better clinical trade-offs.

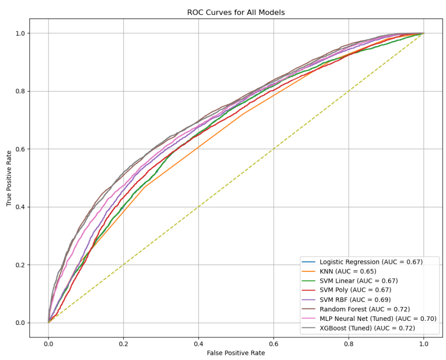


FIGURE 1. ROC curves for all models compared on the CVD dataset using 5-fold cross-validation.

To verify robustness across folds, Fig. 2 depicts per-fold metric variations for the SMNN. The low variance in Acc and F1 confirms stable generalization across splits.

3.4. **Comparative and Ablation Insights.** The comparative analysis (Fig. 3) demonstrates that nonlinear stacking via the ANN meta-learner enhances recall and $F_1$ balance compared to linear Logistic Regression meta-fusion used in prior works [18, 15]. The statistically guided and HEART-refined preprocessing pipeline further contributes to this improvement by reducing redundant or noisy inputs before ensemble training.

Figure 4 shows the aggregated average metrics, highlighting SMNN's balanced trade-off between precision and recall. The model's improved recall performance is particularly valuable for early CVD detection, where false negatives are clinically costly.

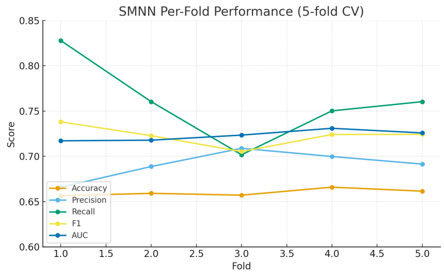


Figure 2. Per-fold performance metrics of the proposed SMNN showing stable generalization.

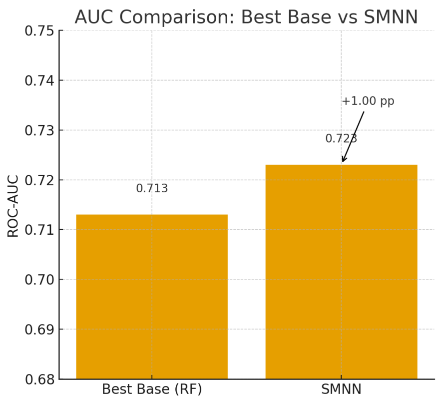


Figure 3. AUC comparison between base learners and SMNN with nonlinear meta-fusion.

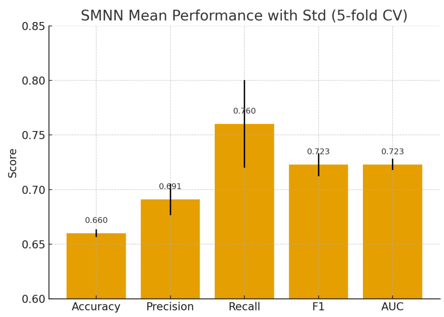


Figure 4. Average cross-validation metrics comparing SMNN with baseline classifiers.

3.5. **Statistical Validation.** The improvement of SMNN over baseline models was statistically validated using paired $t$-tests across folds. Let $\Delta M_i = M_i^{(\text{SMNN})} - M_i^{(\text{Base})}$ represent the metric difference for fold $i$. The test statistic is given by:

$$t = \frac{\bar{\Delta M}}{s_{\Delta M}/\sqrt{k}}, \quad s_{\Delta M} = \sqrt{\frac{1}{k-1}\sum_{i=1}^{k}(\Delta M_i - \bar{\Delta M})^2},$$

where $k = 5$ denotes the number of folds. Results confirmed that improvements in recall and $F_1$ were statistically significant ($p < 0.05$), indicating consistent superiority of the proposed method. The experimental analysis demonstrates that the proposed SMNN achieves stable and clinically meaningful performance improvements. Its hybrid design—combining statistical selection, HEART-based refinement, and nonlinear meta-fusion—provides an interpretable yet powerful framework for scalable cardiovascular risk prediction.

## 4. Discussion

Cardiovascular disease (CVD) is still one of the major global causes of death, accounting for nearly 18 million deaths each year [19]. Traditional prediction models like the Framingham Risk Score and SCORE project [5, 4] have been useful for many years, but they rely on linear assumptions that often fail to capture the complex relationships between clinical and physiological variables. With the recent growth of artificial intelligence (AI) and machine learning (ML), there has been a clear shift toward nonlinear and ensemble-based models that can better describe these intricate medical dependencies [1, 3]. Ensemble learning, and especially stacking, has shown strong ability to merge predictions from multiple algorithms to improve generalization and robustness [18, 15]. As highlighted in the comprehensive reviews by Mohammed and Kora [13] and Mahajan et al. [12], ensemble deep learning is now one of the main directions in intelligent disease prediction. Several recent studies, such as Ganie et al. [7] and Wu et al. [20], have demonstrated that combining ensemble methods with explainable AI (XAI) makes predictive systems more reliable and easier for clinicians to interpret. Similarly, Yoon and Kang [21] have shown that multimodal stacking approaches—using diverse medical data like ECG, biomarkers, and patient history—lead to more stable diagnostic outcomes. These trends align with the broader argument of Holzinger et al. [8, 9], who emphasized that medical AI should not only be accurate but also interpretable enough to earn physician trust. Following this same vision, our proposed Stacked Meta Neural Network (SMNN) incorporates both statistical and HEART-based feature refinement before nonlinear stacking, combining clinical interpretability with computational strength. The findings correspond well with those reported by Natarajan et al. [14], Kumar and Thakur [10], Sultan et al. [16], and Tiwari et al. [17], where nonlinear stacking improved recall and F1 scores more consistently than classical linear meta-fusion. In addition, the optimization-based design of Daza et al. [6] supports the idea that careful hyperparameter tuning and meta-learner selection can enhance generalization across unseen data. Our SMNN framework, through adaptive nonlinear fusion, achieved similar stability and recall improvement trends, reflecting the same robustness patterns observed in these studies. Furthermore, comparable findings by Li et al. [11] and Ashika et al. [2] reinforce that the combination of multimodal learning and explainable stacking strategies not only improves prediction accuracy but also increases clinicians' confidence in AI-based decision support systems. Taken together, these related works and our results underline that integrating explainability, medical reasoning, and nonlinear ensemble fusion is an effective pathway toward practical, trustworthy, and clinically interpretable CVD prediction systems.

## 5. Conclusion

In this work, we introduced a Stacked Meta Neural Network (SMNN) framework that combines statistical analysis, clinical feature refinement, and nonlinear ensemble fusion to improve cardiovascular disease prediction. The experiments showed that by using both statistically and medically validated features together with a nonlinear meta-learning layer, the model achieved better interpretability and stronger predictive performance compared to conventional methods.

## References

[1] N. S. Alghamdi et al. Heart disease prediction using autoencoder and densenet architecture. *Egyptian Informatics Journal*, 28:100559, 2024. URL: `https://www.researchgate.net/publication/386305825_Heart_disease_prediction_using_autoencoder_and_DenseNet_architecture`.

[2] T. Ashika, J. Narayanana, et al. Enhancing heart disease prediction with stacked ensemble and explainable ai. *Frontiers in Digital Health*, 2025. Accessed 2025-10-31. URL: `https://pmc.ncbi.nlm.nih.gov/articles/PMC12222165/`.

[3] Soham Bandyopadhyay, Ananya Samanta, Monalisa Sarma, and Debasis Samanta. Novel framework of significant risk factor identification and cardiovascular disease prediction. *Expert Systems With Applications*, 263:125678, 2025. `doi:10.1016/j.eswa.2024.125678`.

[4] R. M. Conroy, K. Pyörälä, A. P. Fitzgerald, S. Sans, A. Menotti, G. De Backer, D. De Bacquer, P. Ducimetière, P. Jousilahti, U. Keil, I. Njølstad, R. G. Oganov, T. Thomsen, H. Tunstall-Pedoe, A. Tverdal, H. Wedel, P. Whincup, L. Wilhelmsen, and I. M. Graham. Estimation of ten-year risk of fatal cardiovascular disease in europe: the score project. *European Heart Journal*, 24(11):987–1003, 2003. URL: `https://www.sks.sk/system/files/score_project_2003.pdf`.

[5] Ralph B. Sr. D'Agostino, Ramachandran S. Vasan, Michael J. Pencina, Philip A. Wolf, Mary Cobain, Joseph M. Massaro, and William B. Kannel. General cardiovascular risk profile for use in primary care: the framingham heart study. *Circulation*, 117(6):743–753, 2008. URL: `https://www.ahajournals.org/doi/10.1161/CIRCULATIONAHA.107.699579`, `doi:10.1161/CIRCULATIONAHA.107.699579`.

[6] A. Daza et al. Stacking-ensemble hyperparameter optimization for heart disease diagnosis. *Intelligent Medicine*, 2024. Accessed 2025-10-31. URL: `https://www.sciencedirect.com/science/article/pii/S2590123024001476`.

[7] Shahid Mohammad Ganie, Pijush Kanti Pramanik, and Zhongming Zhao. Ensemble learning with explainable ai for improved heart disease prediction based on multiple datasets. *Scientific Reports*, 15:13912, 2025. doi:10.1038/s41598-025-97547-6.

[8] Andreas Holzinger, Chris Biemann, Constantinos S. Pattichis, and Douglas B. Kell. What do we need to build explainable ai systems for the medical domain? *arXiv preprint*, arXiv:1712.09923, 2017. URL: https://arxiv.org/abs/1712.09923.

[9] Andreas Holzinger, Alexander Zimmermann, Hans Müller, and et al. Causability and explainability of artificial intelligence in medicine. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery*, 9(4):e1312, 2019. URL: https://wires.onlinelibrary.wiley.com/doi/10.1002/widm.1312, doi:10.1002/widm.1312.

[10] Shrawan Kumar and Bharti Thakur. Heart disease prediction using a stacked ensemble learning approach. *SN Computer Science*, 6(3), 2025. doi:10.1007/s42979-024-03499-5.

[11] Ping Li, Yifan Hu, and Z.-P. Liu. Prediction of cardiovascular diseases by integrating multi-modal features with machine learning methods. *Biomedical Signal Processing and Control*, 66:102474, 2021. URL: https://www.sciencedirect.com/science/article/pii/S1746809421000719, doi:10.1016/j.bspc.2021.102474.

[12] Palak Mahajan, Shahadat Uddin, Farshid Hajati, and Mohammad Ali Moni. Ensemble learning for disease prediction: A review. *Healthcare*, 11(12):1808, 2023. doi:10.3390/healthcare11121808.

[13] Ammar Mohammed and Rania Kora. A comprehensive review on ensemble deep learning: Opportunities and challenges. *Journal of King Saud University – Computer and Information Sciences*, 35(2):757–774, 2023. doi:10.1016/j.jksuci.2023.01.014.

[14] K. Natarajan et al. Efficient heart disease classification through stacked ensemble. *SN Computer Science*, 5:538, 2024. doi:10.1007/s44196-024-00538-0.

[15] Omer Sagi and Lior Rokach. Ensemble learning: A survey. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery*, 8(4):e1249, 2018. doi:10.1002/widm.1249.

[16] S. Q. Sultan et al. Machine learning-based stacking ensemble model for prediction. *Symmetry*, 17(2):185, 2025. doi:10.3390/sym17020185.

[17] Achyut Tiwari, Aryan Chugh, and Aman Sharma. Ensemble framework for cardiovascular disease prediction. *arXiv preprint*, arXiv:2306.09989, 2023. URL: https://arxiv.org/abs/2306.09989.

[18] David H. Wolpert. Stacked generalization. *Neural Networks*, 5(2):241–259, 1992. doi:10.1016/S0893-6080(05)80023-1.

[19] World Health Organization. Cardiovascular diseases (cvds). https://www.who.int/news-room/fact-sheets/detail/cardiovascular-diseases-%28cvds%29, 2023. Accessed: 2025-10-31. URL: https://www.who.int/news-room/fact-sheets/detail/cardiovascular-diseases-%28cvds%29.

[20] Yuanyuan Wu, Zhuomin Xia, et al. Forecasting heart disease risk with a stacking-based ensemble machine learning method. *Electronics*, 13(20):3996, 2024. Accessed 2025-10-31. URL: https://www.mdpi.com/2079-9292/13/20/3996.

[21] Taeyoung Yoon and Daesung Kang. Multi-modal stacking ensemble for the diagnosis of cardiovascular diseases. *Journal of Personalized Medicine*, 13(2):373, 2023. URL: https://www.mdpi.com/2075-4426/13/2/373, doi:10.3390/jpm13020373.

## Appendix A. SMNN Workflow Diagram

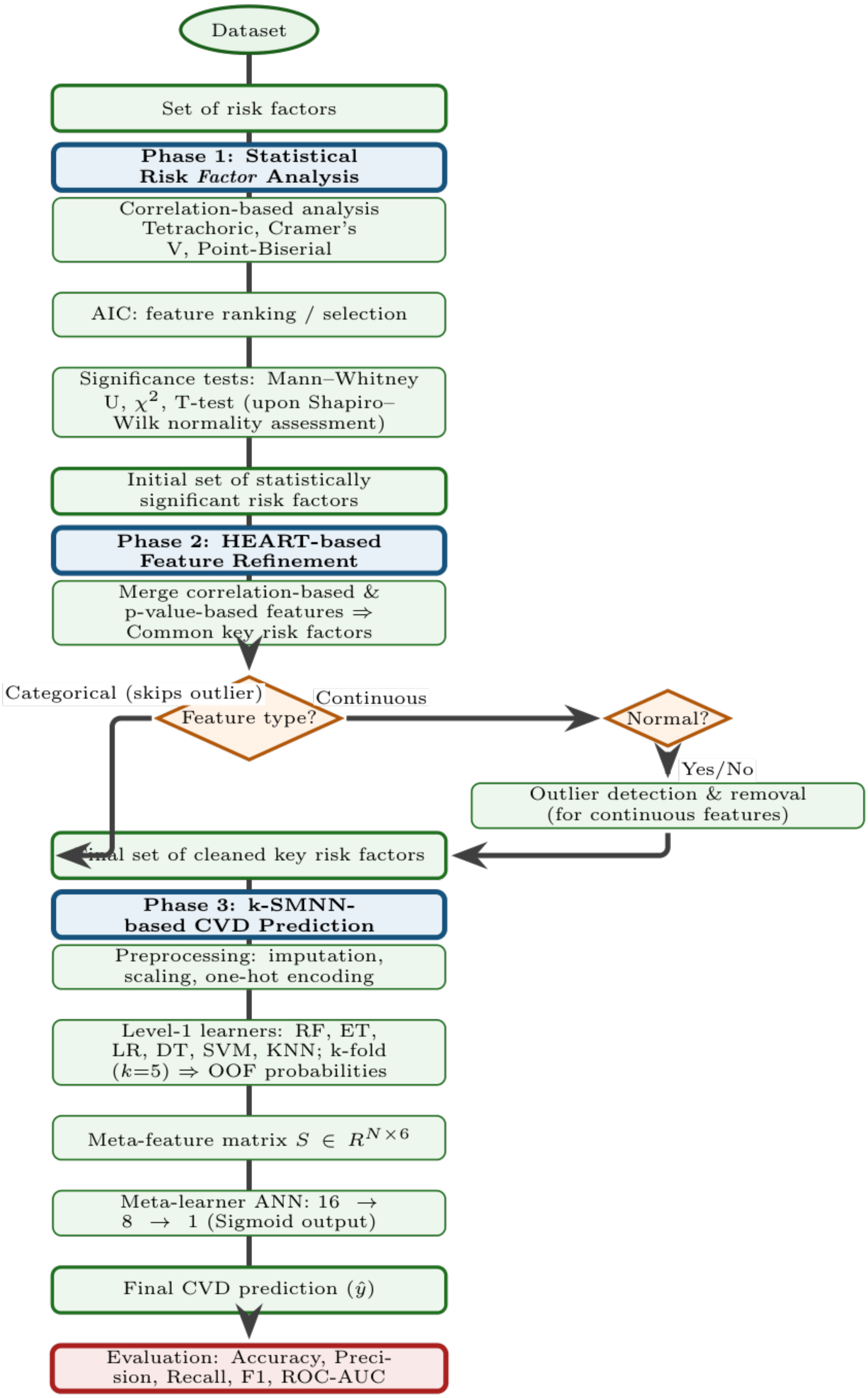


Figure 5. Three-phase workflow of the proposed SMNN framework for cardiovascular disease prediction. Phase 1 performs statistical risk factor analysis, Phase 2 applies HEART-based clinical refinement, and Phase 3 executes stacked meta-learning with nonlinear ANN-based decision fusion.

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# THE DIALOGICAL NATURE OF IWONA CHMIELEWSKA'S PICTUREBOOKS – AESTHETIC AND PEDAGOGICAL CONTEXT

JOANNA STANISŁAWA LUDWICZAK

Abstract. The issue of art for children as a subject of research has a tradition dating back to the beginnings of the aesthetic-pedagogical movement in Europe. One of the contemporary examples of art for children is the picturebook. As an artefact of visual culture, it fits in particularly well with the current issues of aesthetic education for children. The aim of the presented interpretation is to identify the attributes of Iwona Chmielewska's work that are important in the context of a child's encounter with art. The unique form of the phenomenon described, inherent to works of art, responds to the child's natural characteristics and offers them full participation in co-creating the work.

## 1. Introduction

The issue of art for children as a subject of research has been explored since the early 20th century, alongside the development of the aesthetic-pedagogical movement in Europe. This movement was guided by the belief that one of the essential aspects of aesthetic education is an encounter with an authentic work of art. This view permeated pedagogical theory and practice throughout the 20th and 21st centuries. The essence of the child's encounter with a work of art has been discussed in Polish scholarly literature by, among others, Stefan Szuman, Maria Gołaszewska, Bogusław Żurakowski, Katarzyna Olbrycht, and Jolanta Skutnik. This postulate has been, and continues to be, an inspiration for further theoretical considerations and educational activities in the field of culture.

Art does not always occupy its rightful place in contemporary educational practice; it is often treated in a superficial and instrumental manner. Its essence as an end in itself is then lost. Many contemporary educational concepts establish art as one of the pillars of education and emphasize its importance in developing 21st-century competencies. Reflection on visual art as a subject of pedagogical considerations therefore seems to be a current issue, especially in the era of image culture. According to J. Skutnik (2004), "new art cannot be ignored in education. Contrary to appearances, it contains a clear educational and upbringing potential [...] it is a kind of mirror in which contemporary people see themselves [...], each seeking their place in this world, which is their reality" (p. 88). According to the author, the primary educational value of art is not only the conveyance of specific content, but above all, the unique method of communication, achievable exclusively through art (Ibid., p. 86). A necessary condition for the value of art to emerge in education is understanding its dialogical nature and recognizing it as an independent and equivalent value (Ibid., p. 87).

## 2. The picturebook as an art object

A special kind of creativity is art created with the youngest audience in mind. This area is perceived as a valuable medium supporting child development. Its potential is promoted by valuable creative activities undertaken by educators, teachers, and artists in many areas of non-formal education (including the educational activities of cultural institutions, publishing houses, cultural organizations, etc.). Among the many areas of contemporary art for children, the picturebook genre is worth mentioning, representing one of the paths continuing the rich tradition of the Polish School of Illustration (Boguszewska, 2018).

*Classification of fields and disciplines of science and disciplines of the arts in Poland (2022).* Social Sciences: Education.
*Key words and phrases.* Social sciences, education, aesthetic education, Iwona Chmielewska's picturebook, visual research.

Picturebooks (except for textless books) address the reader through two linguistic codes: visual and verbal. However, it is most often the visual layer that dominates the overall message. A crucial feature of the picture book genre is the coherence of the graphic, typographic, and editorial concepts. The narrative is constructed not only through the synergy of image and word, but also through paratext, which encompasses all the details that constitute the book's architecture. Attention to detail and a consistently implemented publishing concept make picturebooks a distinguished work. Lawrence R. Sipe (2001) emphasizes that the harmonious combination of all the elements of a book creates specific sequences and relationships that may prove crucial for the full understanding of the message (p. 24).

Małgorzata Cackowska (2017) notes that: "picturebooks, due to their formal features, are treated as beautiful objects – artifacts" (p. 24) and classifies them as works of art created by the creator "for the recipient and their aesthetic experience" (pp. 14–16). Many scholars, such as Barbara Bader, Barbara Z. Kiefer, Perry Nodelman, Maria Nikolajeva, L.R. Sipe, and others, emphasize the artistic nature of the message and form of picturebooks, considering them works of art. M. Cackowska attributes exceptional artistic value to works in which the image and word originate from the hand of a single author. These books, defined as artists' books are distinguished by "the thread of conscious artistic choices of style and means of expression, as well as the position of the artists in relation to the text, how they change or develop the meaning of the image in the book, what boundaries [...] they cross in the pictorial representation of the world" (Cackowska, 2017, p. 16). This category encompasses a significant portion of the work of Iwona Chmielewska, a renowned Polish illustrator and, above all, creator of picturebooks. Her works constitute an intellectual adventure for researchers from various disciplines, demonstrating that they can be considered on many levels and in various contexts.

## 3. Contexts of an authentic encounter with art

This article focuses primarily on the aesthetic and pedagogical dimensions of picturebooks. The aim of the presented interpretation is to identify attributes of Iwona Chmielewska's work that are important in the context of a child's encounter with art. Citing J. Skutnik (2004, p. 103), the essence of the encounter with art is considered to be the authenticity of the work and a dialogical relationship.

The first category emphasizes the values resulting from contact with authentic art objects. The superiority of original works over copies in an educational context was emphasized by S. Szuman (1975), who wrote that only original works "can lead to the recipients' knowledge, experience, and adequately experience works of art" (p. 118). In this respect, the picturebook exhibits a certain uniqueness. On the one hand, it is undoubtedly a cultural artifact of high aesthetic value. At the same time, however, as an object of applied art, it has the potential to exist in a child's immediate environment, becoming an artifact of everyday life. The dialogical dimension of encountering art suggests an interaction between the creator and the viewer. The narrative, expression, and form of a work, in close relationship, create an open space for multi-level interpretation. This approach to art has been further developed in theories emphasizing the performative dimension of works. Examples include Umberto Eco's theory of open work and Hans Georg Gadamer's dialogical hermeneutics. In both cases, the work is complemented by an encounter with the viewer, understood as a process of interpretation and meaning-making.

The category of dialogicity can also be considered in relation to the features of the work itself. Mikhail Mikhailovich Bakhtin (1984, pp. 6–7) considers the following to be key: polyphony, understood as the coexistence of different, autonomous voices and perspectives; interactivity, or the emergence of meanings in dialogue between the work and the recipient; openness, consisting in the absence of imposed, closed meanings; relationality, referring to the mutual interaction and complementation of the elements of the work's structure; dynamism and actualization of meaning, indicating the processual nature of interpretation; and autonomy of voices, emphasizing the distinct logic and perspective of the individual components of the work. Although the above set was developed based on literary works, its universality allows for the application of these characteristics to visual representations.

As J. Skutnik (2008) writes, "an encounter with art understood as the fulfillment of a dialogical relationship with a work of art may become apparent already in childhood and should accompany an individual throughout life as a kind of permanent experience, implying a deep context of contact with art" (p. 159).

## 4. Subject and method of interpretation

I. Chmielewska's works are characterized by the privileged role of the visual layer, which, in synergy with the words and the entire architecture of the book, together build a narrative. The specificity of the research subject, marked by visuality, is exceptionally amenable to a qualitative research approach (Sztompka, 2012), which seems most appropriate in relation to cultural artifacts. The analysis and interpretation of a work of art, in this case the phenomenon of Chmielewska's picturebook, conducted from a pedagogical perspective assumes its humanistic evaluation (Kubinowski, 2017, p. 18).

The collected research material was analyzed using compositional interpretation, proposed by Gilian Rose as part of a critical approach to visual social studies. The essence of this method is to see "an image for what it is, not for what it does, or how it was or is used" (Rose, 2010, p. 58). A researcher seeking meaning focuses primarily on the image itself and its compositional modality (see Rose, 2010, p. 58). The key to receiving the message is immersion in the language of visual arts, its elements (e.g., line, spot, color, texture, etc.), principles (e.g., types of composition, color palettes), and relationships (e.g., contrasts, harmonies).

Rose (2010) emphasizes that the image itself has the power to influence and therefore requires careful observation. She believes that images attract viewers' attention and, in some way, influence them through their appearance (p. 57). An interpretation based on this understanding of the picture book in relation to its visual and material qualities corresponds to a dialogical approach to the encounter behind art.

The subject of this analysis is Iwona Chmielewska's picturebook. The research sample included 12 artists' books published in Poland between 2006 and 2020 (Chmielewska, 2006, 2011, 2012, 2013a, 2013b, 2014a, 2014b, 2014c, 2015a, 2015b, 2018, 2020). The choice of Iwona Chmielewska was determined by the artist's stature and international recognition in the field of illustration and children's books.

## 5. The openness of a picture book to dialogue with the child

A valuable work of art reflects many characteristics of a child's personality. Among them, J. Skutnik (2004) lists: innate sensitivity and openness, emotional engagement, a willingness to indulge in sensory experiences, spontaneity and freedom in the use of symbols, a searching attitude, the courage to ask questions, authenticity in contact with the Other, and a fascination and curiosity about ordinary things (pp. 103-104). These characteristics can be activated on many levels during a child's encounter with Chmielewska's picturebooks.

A key characteristic of Chmielewska's picturebooks is their openness to the reader. This is reflected in various elements of the book's form and content, which in various ways invite the reader to participate in discovering and adding to the story. The book's narrative is completed through the reader's interpretation, who enriches it with their own experiences, ways of experiencing and understanding reality, as well as their doubts and questions. On the one hand, we are talking about the less tangible aspects of engaging in work, and on the other, about the meanings ascribed to it.

In Chmielewska's books, the author's sensitivity meets that of the potential reader, which is evident in two dimensions: emotionality and sensuality (Ludwiczak, 2024). The book appeals to the realm of feelings and emotions both directly through the content contained in words and images, and indirectly through artistic means. These are revealed through the characters' expressions: gestures, facial expressions, poses, and motifs depicting interpersonal relationships: partnerships, friendships, family, and intergenerational. An example of this depiction of family and generational bonds, as represented by the following excerpt from one of the works:

*From then on, the tablecloth became even more beloved and even more of a souvenir.*

*It is now a memento of my grandmother, my mother, and me.* (Chmielewska, 2012, p.)

The narratives portray the characters in various everyday situations and emotional states. They non-judgmentally emphasize the need to express emotions and feelings and demonstrate the power of self-awareness and the strength of connection. References to emotions are also present in symbols, contexts, and details, dedicated to the viewer's attentiveness. Visual expressions such as color, chiaroscuro, texture, perspective, and composition enhance their impact. They allow the viewer to experience a full range of emotions, encompassed by veiled elements of comedy and tragedy, as well as subtle details of the aesthetics of the past and an atmosphere of intimacy.

An important feature of Chmielewska's work, corresponding to childhood sensory sensitivity, is sensuality (Ludwiczak, 2024). It concerns the ennoblement of the senses in experiencing reality and encourages reflection on their role in life. Themes related to sensory perception are explored in both the visual and literary layers, for example:

*He who sees doesn't even know what a precious treasure he receives as a gift.*

*He simply opens them every day, and they guide him [...]*

*And he can't imagine them not being there. [...]*

*He who doesn't see, receives a different treasure as a gift [...]*

*He can find, what he's looking for. [...]*

*And feel happy like everyone else –*

*He who sees and he who doesn't see.* (Chmielewska 2014c, s.p.)

The illustrations emphasize sensory experiences in depicting everyday, natural, and intimate situations, such as a soothing bath, a walk in a rainy, windy day, farm work, or someone whispering in someone's ear. They engage the imagination and evoke experiences familiar to the viewer: the scent of flowers, the softness of yarn, a gust of wind, the smoothness of a piano keyboard, etc. A common technique in the analyzed picturebooks is the use of close-up shots of fragmented figures, whose presence is indicated only by the images of hands, eyes, and mouths. The artist's craftsmanship lends the books a distinct sensuality. This is evident in the selection of materials used to create illustrations (fabrics, old prints, lace, dried plants, etc.), the color palette (muted and off-kilter hues, including browns, grays, ochres, accents of blue and red), and the artistic technique (collage, sewing, embroidery, crayon drawings, etc.). These elements are complemented by editorial touches that enhance each volume (gilded edges of the book block, cover embossing, cutouts, paper texture). These meticulously crafted pieces, full of subtle details, foster contemplation and emotional and sensual engagement.

A characteristic of Chmielewska's work that responds to a child's natural inclination to freely use symbols is its poetic quality (Ludwiczak, 2024). The narrative form often includes a metaphorical invitation to co-create the work. In this act, the child's joy in action becomes an impulse to experiment with image and text and to complement the narrative through their own interpretive strategies. The poetic quality in Chmielewska's picturebooks encompasses non-literal themes, presenting the world through metaphors and serving as a pretext for asking questions. In these representations, content and form complement each other, jointly creating new meanings. These take the form of multi-layered visual metaphors and, at other times, details marked by symbolism. Examples of metaphorical messages include surrealist motifs, optical illusions, and literary devices such as personification, animation, and periphrasis.

*Pokój szykuje się do snu.*

*Ciemno się robi we wszystkich kątach*

*– Raz dwa trzy cztery* (Chmielewska, 2018, s.p.)

The narrative of many of Chmielewska's works is based on a recurring visual motif (e.g., a silhouette) and the unification of form with ambiguous content. This inspires the viewer to imagine further visual transformations and create new meanings. In many picturebooks, the symbolic space in which the book's narrative can resonate with the viewer's interpretation is provided by the unprinted background spaces. These empty planes emphasize the poetic dimension of Chmielewska's work.

Another significant feature of Chmielewska's picturebooks is relativization, which involves presenting phenomena in a relational and contextual manner (Ludwiczak, 2024). This approach fosters an exploratory attitude, encouraging readers to examine reality from various perspectives and deepen their understanding of observed situations. These themes emphasize openness to difference, multiple perspectives, and the diversity of human experiences. Chmielewska's books feature characters representing a broad spectrum of everyday life: children, the elderly, people with disabilities, as well as historical figures portrayed without pathos, but in a close and human way. They are captured in moments of work, rest, celebrating important moments, sleeping, taking on challenges, etc. Each of these situations is treated with equal attention and contributes significantly to the creation of the narrative. These motifs foster an authentic encounter with the Other, without hierarchizing experiences or simplifying emotions. The diverse emotional states of the characters reveal the ordinariness and complexity of everyday life. They encourage empathy, sensitivity, and attentive companionship with others.

*Gdy dwoje ludzie żyje razem,*

*to jest im łatwiej, bo są razem*

*i jest im trudniej, bo są razem.* (Chmielewska, 2014 s.p.)

Relativization also appears in the formal solutions of Chmielewska's works, for example, in the various ways of capturing depth in the visual layer. In some illustrations, artistic perspective is clearly marked through the use of lines, in others through a backstage arrangement of plane forms. There is also a compositional arrangement in which objects placed centrally against a plain unprinted background appear suspended in an unlimited space. The arrangement of elements on a spread places the viewer in a specific relationship to the representation. This allows the viewer to observe the scene from a specific perspective, for example, from above (bird's-eye perspective), from below (frog perspective), or straight on.

One of the natural childlike tendencies mentioned by J. Skutnik is a fascination and curiosity about ordinary things. Children naturally endow objects with meaning, a consequence of their symbolic and emotional way of thinking. In Chmielewska's picturebooks, everyday artifacts occupy a special place. They play a key role in the narrative centered around human stories. They serve as traces of the past and witnesses to events.

*You can write a book about anything.*

*And anything will be useful in it.*

*Even four ordinary bowls.* (Chmielewska, 2013b, s.p.)

Affirmation of everyday life (Ludwiczak, 2024) explores themes in Chmielewska's work related to the material human environment, everyday activities, and the ennoblement of simplicity. A distinctive feature of Chmielewska's picture books is their consistently developed visual narrative, for example, utilizing the obverse-reverse relationship. The aesthetic conventions of these works often tend toward minimalism and concise form, depicting the world in a realistic manner. Equally characteristic of these works is a tendency toward linearity and flatness. These features largely correlate with the technique and materials used to create illustrations. All works utilize traditional analog techniques such as pencil, crayon, watercolor, and sewing, sometimes woven into collages using fabrics, lace, old prints, dried flowers, yarn, and more. This method of work celebrates the work of human hands, an ethos repeatedly emphasized by the subject matter of the illustrations.

## 6. Concluding Reflection

Iwona Chmielewska's picturebooks are characterized by many categories attributed to contemporary works of art. As J. Skutnik (2004) writes, "new art is the art of our times, our dilemmas, our questions, our aspirations, our fascinations and fears," which is why "her representations are becoming important stimuli for the educational process today" (pp. 103–104). According to K. Olbrycht (1987), the essence of an encounter with art, apart from being subjected to aesthetic experiences, is revealed in the ability to combine experiences and active search for different cognitive perspectives.

I. Chmielewska's picturebooks, as works of art, intertwine two perspectives: the creator's message and the reader's interpretation. These works offer specific ways of looking at the world. They don't provide ready-made answers but rather teach us to ask questions and reflect. They encourage us to be courageous in our subjective experience of the world and to search for our own identity. The message of Iwona Chmielewska's original works is incredibly powerful.

Chmielewska's picturebook, due to its unique attributes, becomes a dialogue partner for the child. This suggests the possibility of an authentic encounter with the work. This artifact becomes a tool for interactive experiences. It breaks the rule of linear narrative reading and encourages the creation of meaning. It also brings to light topics that are uncomfortable, ambiguous, or seemingly trivial. It addresses topics close to the child (and every person), while simultaneously transcending this and enriching the experience. Chmielewska's picturebook is full of respect for each reader. It establishes the child as an equal recipient of art and co-creator of the narrative. It also creates a space for strenghtening the child's subjectivity and sharing the valuable experiences inspired by the book between children and adults.

## References


[1] Bakhtin M. M. (1984). *Problems of Dostoevsky's Poetics*, trans. C. Emerson. Minneapolis: University of Mennesota Press.
[2] Boguszewska A. (2018). *Przyczynek do genezy polskiej książki obrazkowej.* Ars Educandi. 15, pp. 17–30.
[3] Cackowska M. (2017). *Współczesna książka obrazkowa – pojęcie, typologia, badania, teorie, konteksty, dyskursy.* In M. Cackowska, H. Dymel-Trzebiatowska, J. Szyłak (Red.) Książka obrazkowa. Wprowadzenie. pp. 11–48. Poznań: Instytut Kultury Popularnej.
[4] Chmielewska I. (2006). *O wędrowaniu przy zasypianiu.* Warszawa: Hokus-Pokus.
[5] Chmielewska I. (2011). *Pamiętnik Blumki.* Poznań: Media Rodzina.
[6] Chmielewska I. (2012). *Kłopot.* Warszawa: Wytwórnia.
[7] Chmielewska I. (2013a). *O tych, którzy się rozwijali.* Poznań: Media Rodzina.
[8] Chmielewska I. (2013b). *Cztery zwykle miski.* Wrocław: Format.
[9] Chmielewska I. (2014a). *Dwoje ludzi.* Poznań: Media Rodzina.
[10] Chmielewska I. (2014b). *Królestwo dziewczynki.* Warszawa: Entliczek.
[11] Chmielewska I. (2014c). *Oczy.* Wrocław: Warstwy.
[12] Chmielewska I. (2015a). *W kieszonce.* Poznań: Media Rodzina.
[13] Chmielewska I. (2015b). *Abc.de.* Wrocław: Warstwy.
[14] Chmielewska I. (2018). *Kołysanka na cztery.* Lusowo: Wolno.
[15] Chmielewska I. (2020). *Gdzie jest moja córka?* Wrocław: Format.
[16] Kubinowski D. (2017). *Badania pedagogiczne w kalejdoskopie paradygmatów, orientacji, podejść, metod nauk hymanistycznych, społecznych i stosowanych.* In D. Kubinowski, M. Chutoriański (Red.) Pedagogika jako humanistyczno-społeczna nauka stosowana: konsekwencje metodologiczne. pp. 15–24. Kraków: Impuls.
[17] Ludwiczak J. (2024). *Książka obrazkowa Iwony Chmielewskiej jako źródło edukacji estetycznej dziecka* (Unpublished doctoral dissertation). Łódź: Uniwersytet Łódzki, Wydział Nauk o Wychowaniu.
[18] Olbrycht K. (1987), *Sztuka a działania pedagogów.* Katowice: Wyd. Uniwersytetu Śląskiego. Rose G. (2010). Interpretacja materiałów wizualnych. Krytyczna metodologia badań nad wizualnością. Warszawa: PWN.
[19] Sipe L. R. (2001). *Picturebooks as Aesthetic Object. Literacy and Learning*, 1/6, pp. 23–42. Columbus, Ohio: The Literacy Council of North America.
[20] Skutnik J. (2004). *Wychowanie w sztuce jako koncepcja edukacji kulturalnej dziecka.* In K. Olbrycht (Red.) Edukacja kulturalna: wybrane obszary. pp. 78-106. Katowice: Wyd. Uniwersyetu Śląskiego.
[21] Skutnik J. (2008). *Muzeum sztuki współczesnej jako przestrzeń edukacji kulturalnej dziecka.* Katowice: Wyd. Uniwersytetu Śląskiego.
[22] Sztompka P. (2012). *Wyobraźnia wizualna i socjologia.* In M. Bogunia-Borowska, P. Sztompka (Red.), Fotospołeczeństwo. Antologia tekstów z socjologii wizualnej. pp. 11–42. Kraków: Znak.
[23] Szuman S. (1975). *O sztuce i wychowaniu estetycznym.* Warszawa: Wydawnictwa Szkolne i Pedagogiczne.


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# VARIOUS REPRESENTATIONS OF GEOMETRIC OBJECTS IN SPATIAL RELATIONAL AND SPATIAL OBJECT-RELATIONAL DATABASES MANAGEMENT SYSTEMS

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Abstract. In this paper we look at various kinds of representations of geometric objects in spatial relational (or object-relational) database management systems. We confront it with Simple Feature Access and SQL/MM (Part: 3) standards. We also try to find out some other representations of geometric objects that are used not only in traditional spatial database management systems but also in some NoSQL databases. We indicate functions and methods related to geometry representations such as WKT, WKB, GML, GeoJSON, GeoHash, KML, EWKT, EWKB, TWKB, HEXEWKB used in MySQL, Oracle XE and PostGIS/PostgreSQL. We illustrate this with examples, also showing some ideas for importing/exporting geometries between these database management systems.

## 1. Introduction

The establishing in 1999 by Open Geospatial Consortium of the standard for storing and accessing geospatial data in relational databases [30] and then the rise of appropriate ISO standards [21, 22] started the process aimed at achieving the interoperability of different spatial databases, that is, in particular, the ability to communicate and transfer data between these systems that requires the user to have little knowledge about their characteristic features, see [20]. The aforementioned standards (along with subsequent versions, see [41, 42]), force the database management systems that are compatible with these documents to be able to write to the databases spatial attributes of geospatial features given in a specific text format (called Well-known text, briefly: WKT) or in a special binary form (called Well-known binary, briefly: WKB) and also to convert spatial attributes stored already in the databases to these formats. Thanks to this, the transfer of spatial data between different databases has been significantly simplified. It also has started to be much easier to use an unfamiliar spatial relational database management system, because it is not necessary to know the methods of creating geospatial features specific for that system (so called native methods), it is enough to find the appropriate converting functions or constructors based on WKT or WKB representations. These representations are also described in the third part of SQL/MM standard, devoted to spatial data. This standard additionally gives one more possibility: a textual representation of geographic feature in GML language.

All these standards relate to relational databases – databases with roots dating back to the 1970s. They are also used by object-relational database management systems which where first created in the 1990s. But now there are many other models of data and various new database management systems, especially those from NoSQL and NewSQL families. Some of these systems also store and process spatial data, e.g MongoDB, CouchDB, Amazon DocumentDB (document stores), Cassandra (wide-column store), Neo4j (especially with Neo4j Spatial Library) (graph database), Redis (key-value store), Elasticsearch, Solr (search engines), Amazon DynamoDB with Geo Library (document store, key-value store), see [5, 13, 18, 65, 66]. There are papers in which authors attempt to compare geospatial capabilities of relational and NoSQL databases or analyse performance of the queries in such databases [7, 3, 4, 8, 59, 27] or even try to present some hybrid (NoSQL-SQL) approach [19]. Therefore a very important question arises whether it is possible to talk about the interoperability of traditional (i.e. spatial relational or spatial object-relational) and new types of databases. However, in this

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paper we do not try to answer it (for instance authors of [6] showed some possibilities to interoperate spatial data stored in SQL and NoSQL databases via OGC services using GML format) or to consider these new types of systems or their capabilities, but we emphasise the fact that the representations of geometric objects used in them, especially GeoJSON, infiltrated the relational or object-relational databases and became an important way to represent such objects there. Extending the capabilities of relational or object-relational systems to the processing and use of these newer formats not only allows these systems to compete in some respects with NoSQL systems, but also could be an opportunity to build some interoperability and make the export and import of geospatial data easier. In Section 2 of the paper, we firstly look carefully at different versions of above-mentioned standards and try to find in them all methods and functions connected with representations of the spatial attributes of geospatial features. Then we point out various other representations of the geospatial data, such as GeoJSON or GeoHash. In Section 3, we will look at three of leading spatial relational / object-relational database management systems (Oracle, MySQL and PostgreSQL with PostGIS), checking if they implement the methods, converting functions and constructors required by the standards and whether they provide others representations, especially those that are also used in NoSQL systems. Section 4 includes some examples to demonstrate how the discussed functions and methods work.

## 2. Various representations of geometric objects

### 2.1. Representations of geometric objects described in international standards connected with storing and retrieving spatial or geospatial data in relational databases.

2.1.1. *"Simple Feature Access" Standard.* The first standard concerning spatial data in databases was OpenGIS Simple Features Specification For SQL, from 1999 (let us call it SF standard, for brevity) [30]. In 2005, it was superseded by OpenGIS Implementation Specification for Geographic information – Simple feature access, known widely as "Simple Feature Access" (briefly: SFA standard). The SFA standard consists of two parts – Part 1: Common architecture [41] and Part 2: SQL option [42] and is compatible with ISO 19125 standard [21, 22]. In these standards the geospatial features have both spatial and non-spatial attributes. The values of the spatial attributes are described in terms of geometries – geometric objects such as points, curves, and surfaces (called geometric primitives) or homogeneous or heterogeneous collections of such elements. The so-called simple features are based on two-dimensional geometries with linear interpolation between vertices. Each geometric object is associated with a number identifier, called Spatial Reference System ID (abbreviated as SRID), which identifies the coordinate space in which the object is defined. The documents are based on an extended Geometry Model, in which geometries form an appropriate hierarchy of classes, with Geometry class as a root. Some of these classes are non-instantiable ones – it is impossible to create their instances, they only serve as base classes for their subclasses and define a set of methods for them to inherit. Standards describe the classes in detail along with the attributes, methods and assertions for each class. They also provide the Dimensionally Extended Nine-Intersection Model, some methods for testing spatial relations between geometric objects, some methods that support spatial analysis, WKT and WKB representations of geometric objects, Well-known Text Representation of Spatial Reference Systems and define sets of supported units, spheroids, geodetic datums, prime meridians, and map projections.

The tables whose rows contain geospatial features are called feature tables. Each feature is stored in one row of the table. The non-spatial attributes of features are stored in columns of a feature table whose types are drawn from the set of standard SQL data types. The way the spatial attributes are stored depends on a chosen implementation. The standards propose three possible ways (all with ODBC access in SF standard or SQL/CLI access in SFA). In the first two cases, geometries are stored in an additional table (called a geometry table) by means of numeric (respectively: binary) SQL types (using WKB representation of geometry in the second case). In the third case, geometries are stored in the feature table using SQL Geometry types – types that extend the standard set of SQL data types via Abstract Data Types and are based on the extended Geometry Model. In all these cases, standards require the existence of appropriate metadata views: one containing information about available coordinate systems and the second containing information about feature tables stored in the database. Both SF and SFA standards tell us about two representations of geometry that can be used both to create new instances and to convert existing ones: the text representation (so-called Well-known Text representation, briefly: WKT representation) and binary representation (so-called Well-known Binary representation, briefly: WKB representation). Thanks to the WKB representation, the geometry is presented as a contiguous stream of bytes. This stream arises by changing to bytes a sequence of numbers describing a given geometry and the way it is being described. In particular numbers indicate the order of bytes in the stream, the geometry type and the geometry coordinates. The Well-known Text representation of geometry presents it as a text composed of type names, brackets, commas and numbers indicating geometry coordinates. The way the text should be created is described by special grammar rules described in BNF notation. Both of these representations do not include information about the coordination system and both are defined for the geometric elements described in a given standard, formally for each geometry type, but in practice the grammar or structure of it is defined only for geometries belonging to instantiable subclasses of the Geometry class.

Therefore the SF standard describes details of these representations for zero-, one- or two-dimensional geometries existing in two-dimensional coordinate space, belonging to Point, LineString, Polygon, GeometryCollection, MultiPoint, MultiLineString or MultiPolygon class, assuming linear interpolation between vertices of the elements. Among the methods for the Geometry class there are methods exporting a given geometry to WKT or WKB representation (`AsText` and `AsBinary` method, respectively).

In order to be compliant with the SF standard a database management system should implement functions having capabilities such as those described in Table 1. Systems can also implement some optional functions that support Polygon or MultiPolygon type elements creation given an arbitrary collection of possibly intersecting rings or closed LineString values (see Table 2).

In the first version of SFA standard (version 1.1 from 2005, [31, 32]), the coordinate dimensions of geometries, the hierarchy of classes and the functions connected with WKT and WKB formats remained the same as in SF. In version 1.2.0 (from 2006, [33, 34]) and in the latest one (version 1.2.1 from 2010–2011, [36, 35]), the instantiable subclasses of Geometry class are restricted to zero-, one- or two-dimensional geometric objects that exist in two-, three- or four-dimensional coordinate space (one can also consider the altitude and/ or the measure and therefore achieve coordinate dimension of geometries equal to 3 or 4). There is also a wider set of subclasses with Triangle, Polyhedral Surfaces and TIN; all still limited to the linear interpolation between vertices in all existing subtypes. The Polyhedral Surface class is mentioned in both parts of the standards, the Triangle and TIN classes - only in the first parts. Part 1 also defines semantics for WKT and WKB representations of geometric objects for all instantiable classes and presents `AsText` and `AsBinary` methods. Part 2, related to SQL-implementation, presents the SQL routines:

- `ST_AsText` and `ST_AsBinary` (for obtaining, respectively, the WKT and WKB representation of a geometric object),
- `ST_WKTToSQL` and `ST_WKBToSQL` (used to construct geometric objects from, respectively, their WKT and WKB representation).

These routines are specified in SQL/MM.

2.1.2. *SQL/MM Standard.* SQL/MM (actually: SQL Multimedia and Application Packages) is an ISO standard (ISO/IEC 13249-3) with Part 3: Spatial, which defines the way of storing, retrieving and processing spatial data using the SQL language. The first version of that standard was published in 1999. It is based on a hierarchy of geometry types, similar to the hierarchy of geometry classes defined in SFA standard, but with more types. In particular in the latest, fifth edition from 2016 [24], there are also types for different kinds of curves (for instance: geodesic curves and NURBS), types for geometries with various kinds of interpolation between vertices (for instance: elliptical, clothoid and spiral), a type for circles, types for geometries with vertices connected by circular arcs or by both circular arcs and line segments, types for some kinds of solids and compound surfaces (that is instantiable types such as: ST_GeodesicString, ST_NURBSCurve, ST_EllipticalCurve, ST_Clothoid, ST_SpiralCurve, ST_Circle, ST_CircularString, ST_CompoundCurve, ST_CurvePolygon, ST_BRepSolid, ST_CompoundSurface). The instantiable subtypes of the ST_Geometry type (the root class of the hierarchy) are, as in later version of SFA standard, zero-, one- or two-dimensional geometric objects that exist in two-, three- or four-dimensional coordinate space.

The SQL/MM standard describes:

- `ST_WKTToSQL`, `ST_WKBToSQL`, and `ST_GMLToSQL` methods returning a geometry value for a given WKT / WKB / GML representation, respectively, and `ST_AsText`, `ST_AsBinary`, `ST_AsGML` methods that provide respectively the WKT /WKB / GML representation of a given geometry,
- functions `ST_GeomFromText`, `ST_GeomFromWKB`, `ST_GeomFromGML` taking a WKT / WKB / GML representation of a geometry or such representation and a SRID identifier and returning a geometry value for that representation,

- three functions for each instantiable type that take respectively a WKT / WKB / GML representation of a geometry of an appropriate type (or a representation and a SRID identifier) and return a geometry value of an appropriate type (e.g. `ST_PointFromText`, `ST_PointFromWKB`, `ST_PointFromGML`, `ST_LineFromText`, `ST_LineFromWKB`, `ST_LineFromGML`, `ST_CircularFromTxt`, `ST_CircularFromWKB`, `ST_CircularFromGML`, etc.) and additionally functions `ST_BdPolyFromText`, `ST_BdPolyFromWKB`, and `ST_BdMPolyFromText`, `ST_BdMPolyFromWKB` that take a WKT / WKB representation of geometry of ST_MultiLineString value (or such representation and a SRID) and return a geometry value of ST_Polygon (respectively: ST_MultiPolygon) type.

That means that SQL/MM standard uses not two, as SF/SFA standards, but three kinds of representation of geometries: WKT, WKB and GML. The GML is an XML-based language (i.e. a markup language) designed for expressing geographical features (see [39, 29, 10]). It provides a textual representation that can be used for storing or transporting geometries. GML is defined by Open Geospatial Consortium and OGC maintains its standards. In 2007 GML was also adopted as an International Standard (ISO 19136:2007) [23]. The latest ISO standard for GML was established in 2020 [25].

It is also worth mentioning that not only RDBMSs use discussed formats – or instance there are some NoSQL databases that also support WKT format (e.g. Elasticsearch, Solr or Neo4j) or even store geospatial features in WKT (e.g. DataStax Enterprise 6.0 based on Cassandra [11]).

Let us also notice that names of all types, methods, and functions (as well as tables and views) connected with spatial data defined in SQL/MM have the prefix ST, originally stood for "Spatial and Temporal", now interpreted as "Spatial Type". The same prefixes can be found in the newest versions of SFA standard, which shows that these documents refer to the SQL/MM document. A comparison of Simple Feature Access/SQL and SQL/MM – Spatial (2003) can also be found in part 2 of SFA (see Table B 1 in [35]). The SQL/MM standard also describes some other features such as Topology-Geometry and Topology-Network models and types, functions and methods connected with Linear Referencing System. Since not only geometries or spatial references systems have a well-known representation (but also elements of types related to angles, directions, vectors and linear referencing system), therefore the document contains specification of some other functions constructing appropriate elements from its WKT, WKB or GML representation.

At the end of this section, let us note a problem that arises despite the existence of the mentioned standards - namely the problem with the order (or else with an interpretation) of the X and Y values in coordinate tuples, especially in the case of geographic coordinate systems. In SF/SFA standards there is no information about the meaning of the X and Y coordinate in WKT representation, so there is no general guideline as to whether latitude or longitude goes first. That problem is wider, it concerns not only the WKT representation of geometries, but many domains recording the position of objects (see [50, 14]) and can cause troubles especially during exporting and importing data between different systems. The standards give only one clue: it is the SRID identifier that gives meaning to the coordinates and allows to interpret these values properly (see 6.2.3 in [35]).

2.2. **Other representations of geospatial features.** The WKT, WKB and GML formats are not the only ways to represent the geospatial features. The NoSQL databases most often (or mainly) use a different representation – GeoJSON format. GeoJSON is an open standard format that is intended for encoding and interchanging the geographic features [1]. It's latest standard specification (The GeoJSON Specification (RFC 7946)) comes from 2016 [9]. GeoJSON is based on JSON (JavaScript Object Notation) – lightweight, text-based, language-independent data-interchange format derived from JavaScript [2, 12]. JSON is widely used in many NoSQL databases, there are systems based on storing data just in this format (e.g. MongoDB), but for a few years it is also adopted by relational and object-relational databases, that can now store, index and query JSON data (for instance MySQL, Oracle, PostgreSQL, SQL Server, etc.) using native or new, dedicated, data types. In certain applications, JSON has replaced XML, in documentation and on websites (see [43, 26, 58] for instance) some comparison between JSON and XML can be found, with pros and cons of both these solutions. GeoJSON supports geometries with some additional properties (so-called Feature objects), the sets of features (the FeatureCollection objects) and Point, LineString, Polygon, MultiPoint, MultiLineString, and MultiPolygon types. There is also an extension of GeoJSON format, called TopoJSON [15], that is designed for geospatial topologies encoding. It is worth mentioning that GeoJSON is not maintained by any standards organization.

Another format used both in relational, object-relational and NoSQL databases is GeoHash. GeoHash system [64] encodes a geographic location given by latitude/longitude as a string of letters and digits. It uses space-filling curves, transforms the latitude and longitude coordinates space into a hierarchical discrete grid, and assigns the location values 0 or 1 depending on which grid fields it belongs to on the subsequent levels. Then the string of bits is transformed into a shorter string composed of alphanumeric characters. The resulting string represents a rectangular area, the precision of rectangle increases with the length of the string. This technique also allows to move from two-dimensional to one-dimensional data and is used to build so called geohash-based spatial indexes (see [61, 28], for instance).

Some database systems (e.g. Oracle, PostGIS/PostgreSQL or Splunk) also provide support for a KML format. KML (Keyhole Markup Language) is a XML-based language used to display geographic data in Earth browsers, originally developed for Google Earth, but now used in many other tools and mapping websites [40]. It has been an international standard of the OGC since 2008.

## 3. Functions and methods connected with various representations of geometric objects in MySQL, Oracle and PostGIS/PostgreSQL

The first four places in the popularity ranking of relational databases prepared on the db-engines.com website (see [60]) have been occupied for many years by Oracle, MySQL, Microsoft SQL Server and PostgreSQL. Each of these systems is able to store and process spatial data or has special modules, extensions or tools which are able to do that. Let us check what functions and methods intended for representing geometric objects can be found in selected three of these systems (together with modules, extensions, and tools). Let us consider MySQL RDBMS (version 8), Oracle XE with Oracle Spatial and Graph (version 21c) and PostgreSQL (version 14) with PostGIS module (version 3.4).

3.1. **MySQL.** The open-source relational database management system MySQL follows SFA standard (Part 2: SQL Option) (previously followed SF), but it is not fully compatible with any of its versions (see Section 11.4 in [47]). It implements only a subset of a set of geometry types described in SFA, with geometric objects that exist only in two-dimensional coordinate space, and it does not implement the whole required functionality. It enables the creation, storage and analysis of geographic features in four of its engines: MyISAM, InnoDB, ARCHIVE and NDB (with spatial indexes in the first two of these engines). For many years MySQL did not support different coordinate systems and did not provide appropriate metadata views. Even if it was possible to assign to the geometry a SRID identifier, it did not affect anything, the calculations were done assuming Cartesian coordinates. In version 8.0 the things have changed: metadata views (for coordinate systems and feature tables) have been added, as well as a support for geographic computations [56, 57]. Tables, spatial indexes and functions are now "SRID aware" (the InnoDB engine permits both Cartesian and geographic coordinates systems now, MyISAM only Cartesian ones). Most spatial functions (but not all) are able to do proper calculations in case of geographic coordinates [56]. The database documentation [47] says that both SFA and SQL/MM standards are important for MySQL implementation of spatial operations, and for implementation of functions and structure of the metadata views.

MySQL has spatial data types that correspond to SF classes, that is: GEOMETRY, POINT, LINESTRING, POLYGON, MULTIPOINT, MULTILINESTRING, MULTIPOLYGON and GEOMETRYCOLLECTION. MySQL supports standard spatial data formats: WKT and WKB (see Table 3 for functions associated with these two formats). Internally, it stores geometry similarly to WKB format, but with an initial 4 bytes to indicate the SRID value. MySQL also ensures functions connected with GeoJSON and GeoHash representations (see Table 4). However, it lacks functions connected with GML and KML.

3.2. **Oracle object-relational database.** Oracle enables spatial data storing and processing thanks to Oracle Spatial and Graph [48, 49, 44, 45, 46] – a module that includes advanced features not only for vector spatial data with spaghetti data model, but also for topologies, networks, rasters and social and semantic graphs. The module contains MDSYS schema that defines the storage, syntax, and semantics of supported geometric data types, spatial indexing mechanism, Linear Referencing System, support for topological and network models, GeoRaster, support for TIN and NURBS and subprograms for performing spatial queries, spatial analysis and some tuning and utility works. Until December 2019, the full set of Oracle Spatial and Graph capabilities was available only as a paid option in Oracle Database Enterprise Edition, whilst a selected part of it – collected in the so-called Oracle Locator – was available in other versions, especially in a free Oracle Database Express Edition. Since that time all Oracle Spatial and Graph capabilities are available with all editions of Oracle Database, and information about Oracle Locator has been removed from the documentation (see Section Changes in Oracle Database Release 21c in [49]). Oldest versions of Oracle Spatial and Graph (starting with Oracle Database release 10g (version 10.1.0.4) implemented SF standard (with Geometry Types Implementation) (see Section 1.21 in [49]). The newer versions (18c, 19c) are compliant with Part 2 of the SFA

Types and Functions, version 1.1, Oracle Spatial 21c is compliant with Types and Functions version 1.2.1 [38]. Oracle Spatial and Graph also supports the use of types specified in SQL/MM, Part 3. (see the beginning of Chapter 3 in [49]).

Oracle Spatial and Graph provides two geometry types: SDO_GEOMETRY (its native type) and ST_GEOMETRY (based internally on SDO_GEOMETRY, but with many additional static and member functions). The documentation (see Section 3.1 in [49]) says that the Oracle Spatial and Graph SDO_GEOMETRY and the ST_GEOMETRY type from SQL/MM standard with all its subtypes (ST_POINT, ST_CURVE, ST_LINESTRING, ST_CIRCULARSTRING, ST_COMPOUNDCURVE, ST_SURFACE, ST_POLYGON, ST_CURVEPOLYGON, ST_GEOMCOLLECTION, ST_MULTIPOINT, ST_MULTICURVE, ST_MULTILINESTRING, ST_MULTISURFACE, ST_MULTIPOLYGON) are essentially interoperable. The list of SQL/MM functions compared with their counterparts from Oracle Spatial and Graph can be found in Section 3.2 in [49].

The easiest way to obtain a WKT, WKB, GML, GeoJSON or KML representation of a geometry stored as SDO_GEOMETRY is to use object's methods such as:

- `GET_WKT` (returning a CLOB),
- `GET_WKB` (returning a BLOB),
- `GET_GML`, `GET_GML311` and `GET_GML321` (returning a CLOB, all with no input arguments or with SRSNAMESPACE and SRSNSALIAS input arguments (as VARCHAR2) or with COORDORDER input argument (as NUMBER) or with SRSNAMESPACE, SRSNSALIAS and COORDORDER input arguments),
- `GET_GEOJSON` (returning a CLOB),
- `GET_KML` (returning a CLOB).

To create an SDO_GEOMETRY object from well-known textual or binary representations of a geometry, one can use:

- a constructor for that type taking a WKT (as a CLOB) and a SRID (as a NUMBER, with default NULL value),
- a constructor for that type taking a WKT (as a VARCHAR2) and a SRID (as a NUMBER, with default NULL value),
- a constructor for that type taking a WKB (as a BLOB) and a SRID (as a NUMBER, with default NULL value).

But one can also take advantage of functions related to the WKT, WKB, GML, GeoJSON, JSON or KML representation of geometries included in SDO_UTIL package (see Table 5 and Table 6).

Oracle Spatial and Graph also contains functions that validate geometries inputs in WKT and WKB formats: `SDO_UTIL.VALIDATE_WKTGEOMETRY` and `SDO_UTIL.VALIDATE_WKBGEOMETRY` (the first taking a WKT representation as a CLOB or as a VARCHAR2 and the second taking a WKB representation of geometry as a BLOB). These functions return string TRUE if the input is valid (i.e. have the appropriate syntax, consistent with OGC documents) and FALSE otherwise.

Oracle also supports geohashes through subprograms from SDO_CS package (see Table 7). Unfortunately tests done by the author in Oracle XE 21c database (using SQL* Plus) show that the `SDO_CS.FROM_GEOHASH` function returns geometry with invalid GTYPE and needs some corrections. Package SDO_CS also includes `SDO_CS.GET_GEOHASH_CELL_HEIGHT` and `SDO_CS.GET_GEOHASH_CELL_WIDTH` subprograms that take a length of the geohash string and return the cell height (the cell width, respectively) of that geohash.

As mentioned at the beginning of this section, Oracle Spatial also has a second type for storing geometries, namely ST_GEOMETRY type. This type also has methods connected with the representations of geometries, such as:

- `GET_WKB` (returning a BLOB),
- `GET_WKT` (returning a CLOB),

and static functions such as:

- `FROM_WKT` taking a WKT representation (as a CLOB or a VARCHAR2) or WKT representation and a SRID (as a NUMBER) and returning an ST_GEOMETRY object,
- `FROM_WKB` taking a WKB representation (as a BLOB) or a WKB representation and a SRID (as a NUMBER) and returning an ST_GEOMETRY object,

- `ST_ASTEXT` taking a geometry (as a ST_GEOMETRY) and returning a WKT representation (as a CLOB),
- `ST_ASBINARY` taking a geometry (as a ST_GEOMETRY) and returning a WKB representation (as a BLOB),
- `ST_GEOMFROMTEXT` taking a WKT representation (as a CLOB) or a WKT representation and a SRID (as a NUMBER) and returning an ST_GEOMETRY object,
- `ST_GEOMFROMWKB` taking a WKB representation (as a BLOB) or a WKB representation and a SRID (as a NUMBER) and returning an ST_GEOMETRY object.

Moreover for the elements of ST_GEOMETRY type one can also use functions:

- `OGC_ASBINARY` (returning a BLOB with a WKB representation) and `OGC_ASTEXT` (returning a VARCHAR2 with a WKT representation),
- `OGC_POINTFROMTEXT`, `OGC_LINESTRINGFROMTEXT`, `OGC_POLYGONFROMTEXT`, `OGC_MULTILINESTRINGFROMTEXT`, `OGC_MULTIPOLYGONFROMTEXT` (taking a WKT representation (as a VARCHAR2) and a SRID (as a NUMBER(38), default NULL) and returning an ST_GEOMETRY object),
- `OGC_POINTFROMWKB`, `OGC_LINESTRINGFROMWKB`, `OGC_POLYGONFROMWKB`, `OGC_MULTILINESTRINGFROMWKB`, and `OGC_MULTIPOLYGONFROMWKB` (taking a WKB representation (as a VARCHAR2) and a SRID (as a NUMBER(38), default NULL) and returning an ST_GEOMETRY object),

belonging to MDSYS schema.

Summarizing, it follows that Oracle Spatial supports WKT, WKB, GML, KML, JSON, GeoJSON and GeoHash formats (with some problems with the last one). It is worth mentioning that when displaying the contents of a geometric column, Oracle uses either a text containing a call to the native constructor of SDO_GEOMERTY type (for instance in SQL Developer or SQL* Plus) or a GeoJSON format (for instance in Oracle Live SQL). That native constructor call (containing the name of the type, brackets, commas and values for object's fields: SDO_GTYPE, SDO_SRID, SDO_POINT, SDO_ELEM_INFO, SDO_ORDINATES) in author's opinion can be treated as the next representation of geometry, specific to this system only.

3.3. **PostgreSQL & PostGIS.** PostgreSQL, an open-source object-relational database management system, possesses its own, very specific set of a geometry types, with point, line, lseg, box, (open and closed) path, polygon, and circle type [62]. The elements of these types exist in two-dimensional coordinate space. Each type has a few textual representations for its elements - they also could be recognized as a type of geometry representation (very specific one, with many possible ways to describe one given element). PostgreSQL provides geometric functions and operators for these elements. However, it does not provide any metadata and coordinate systems, and does not follow any standards. Nevertheless, the whole thing changes when we start to use PostgreSQL together with PostGIS. PostGIS is an extension to the PostgreSQL DBMS which enables it to store, index, manage and analyse geographic data due to the standards and provides a lot of useful functions and procedures [53, 55]. As of version 0.9, released in September 2004, it supports all objects and functions included in SF standard (see Section 4.1 in [52]). PostGIS 3.0 (Crunchy Data) is compliant with SFA - Part 2 (versions 1.1 and 1.2.1) Types and Functions [37] (same was PostGIS 2.5). Moreover, PostGIS definitely extends that standard because it supports TIN and Polyhedral Surfaces (from version 2.0), allows geometries compound of arcs or containing both arc and linear segments (CIRCULARSTRING, COMPOUNDCURVE, CURVEPOLYGON, MULTICURVE, MULTISURFACE), provides some functionality connected with Linear Referencing System, with topologies and rasters. PostGIS also follows SQL/MM standard. Each of the functions or methods implementing elements from standards are provided with an appropriate precise comment in the documentation.

PostGIS possesses two basic types for geometric object – geometry (older one, with more functions defined on it) and geography. Calculations on elements written using geometry type are done in Cartesian coordinate system. Geography type uses geographic coordinates and supports only geometries from POINT, LINESTRING, POLYGON, MULTIPOINT, MULTILINESTRING, MULTIPOLYGON and GEOMETRYCOLLECTION classes. It does not support curves, and elements of TIN or POLYHEDRALSURFACE class. PostGIS also has types for boxes: box2d and box3d, and geometry_dump type – a composite type used to describe the parts of complex geometry. As compatible with the SFA/SF standards, PostGIS not only supports WKT and WKB formats, but also extends them to EWKT and EWKB formats (Extended Well-Known Text/Binary) that contain SRID information (which standards do not allow). EWKB and EWKT formats are used for the "canonical forms" of PostGIS data objects. The documentation (see Section 4.2.1 in [54]) says that every valid OGC WKB/WKT is also valid EWKB/EWKT, however one should not rely on this, because it can change in the future. PostGIS also uses HEXEWKB representation, that is in the hexadecimal numeral system (i.e. hex-encoded EWKB) and TWKB representation (Tiny Well-Known Binary, that is a compressed binary format aimed at minimizing the size of the output).

PostGIS provides many functions connected with WKT, EWKT, WKB, EWKB, HEXEWKB and TWKB formats (see Table 8 and Table 9). Let us notice that some of the presented functions (for instance `ST_GeomFromEWKT`) support types such as Circular Strings and Curves, Polyhedral Surfaces, Triangles and TINs. PostGIS also manages functions connected with GML (with support for versions 2 and 3), with GeoJSON, KML and GeoHash, see Table 10.

PostGIS also has some others geometry input or output functions that one can also consider as certain kinds of representations, for instance:

- `ST_AsLatLonText` taking a point in a latitude/longitude projection (as a geometry value) and a parameter describing the output format and returning a text with the Degrees, Minutes, Seconds representation of the given point due to the required format,
- `ST_AsEncodedPolyline` taking a Linestring geometry value (as a geometry type) and some optional parameter and returning text containing the geometry as an Encoded Polyline (string with series of coordinates produced by certain lossy compression algorithm [17]),
- `ST_LineFromEncodedPolyline` taking a text with Encoded Polyline and creating a LineString from it (as a geometry type),
- `ST_AsX3D` taking a geometry value (as a geometry type) and two optional parameters and returning a text with a geometry in X3D xml node element format,
- `ST_AsSVG` taking a geometry value (as a geometry type) and two other optional integer parameters and returning the geometry as Scalar Vector Graphics (SVG) path data (as a text).

One can see that PostGIS with PostgreSQL provides the greatest number of supported formats including WKT, WKB, EWKT, EWKB, TWKB, HEXEWKB, GML, GeoJSON, GeoHash and KML.

A summary for all systems discussed can be found in Table 11.

## 4. Examples

Let us consider a table CITIES storing information about 10 cities of Poland with the largest population (in 2021). The columns of the table are:

- id (primary key of the table, storing integers),
- name (column with not null constraint, storing variable-length character strings with maximum 50 characters),
- population (column with not null constraint, storing integers),
- location (column with not null constraints, storing geometries).

We regard each city as a point geometry, built on the basis of the given latitude and longitude values.

Firstly let us use the EXAMPLE database created in MySQL DBMS (version 8.0.27, installed within WampServer 3.2.6) by executing in MySQL console a statement shown in Listing 1.

Listing 1. Creating the EXAMPLE database in MYSQL

```
CREATE DATABASE examples;
```

In that database let us create the table cities (with AUTO_INCREMENT attribute on id column), using InnoDB engine and WGS84 coordinate system having SRID equal to 4326, see Listing 2.

Listing 2. Creating the cities table

```
USE examples;

CREATE TABLE cities (
id INTEGER AUTO_INCREMENT,
name VARCHAR(50) NOT NULL,
population INTEGER NOT NULL,
location GEOMETRY NOT NULL SRID 4326,
CONSTRAINT cities_PK PRIMARY KEY(id)
) engine=INNODB;
```

Choosing the definition of the coordinate system with an appropriate SRS_ID (see Listing 3), we can find out that the axis with a latitude value precedes in that coordinate system the axis with a longitude value.

LISTING 3. Definition of the coordinate system with SRS_ID

```
SELECT definition
FROM INFORMATION_SCHEMA.ST_SPATIAL_REFERENCE_SYSTEMS
WHERE SRS_ID = 4326;

+----------------------------------------------------------------------------+
|DEFINITION                                                                  |
+----------------------------------------------------------------------------+
| GEOGCS["WGS 84",DATUM["World Geodetic System 1984",SPHEROID["WGS 84",6378137, 298.257223563,
    AUTHORITY["EPSG","7030"]],AUTHORITY["EPSG","6326"]],PRIMEM["Greenwich",0,AUTHORITY["EPSG","8901
    "]],UNIT["degree",0.017453292519943278, AUTHORITY["EPSG","9122"]],AXIS["Lat",NORTH],AXIS["Lon",
    EAST],AUTHORITY["EPSG","4326"]]                                     |
+----------------------------------------------------------------------------+
1 row in set (0.05 sec)
```

Let us now fill the table cities with the data obtained on the basis of the information contained in [16] (population of the cities) and [51] (latitude and longitude of the cities). Using given latitude and longitude of the cities let us build the appropriate WKT representations and take advantage of `ST_PointFromText` function that converts a WKT representation to POINT geometry, see Listing 4.

LISTING 4. Insert statements to the table cities in MySQL database

```
INSERT INTO cities (name , population , location) VALUES
('Warszawa', 1860281, ST_PointFromText('POINT(52.12 21.02)', 4326)),
('Kraków', 800653, ST_PointFromText('POINT(50.03 19.57)', 4326)),
('Wrocław', 672929, ST_PointFromText('POINT(51.07 17.02)', 4326)),
('Łódź', 670642, ST_PointFromText('POINT(51.47 19.28)', 4326)),
('Poznań', 546859, ST_PointFromText('POINT(52.25 16.55)', 4326)),
('Gdańsk', 486022, ST_PointFromText('POINT(54.22 18.38)', 4326)),
('Szczecin', 396168, ST_PointFromText('POINT(53.26 14.34)', 4326)),
('Bydgoszcz', 337666, ST_PointFromText('POINT(53.07 18.00)', 4326)),
('Lublin', 334681, ST_PointFromText('POINT(51.14 22.34)', 4326)),
('Białystok', 294242, ST_PointFromText('POINT(53.08 23.10)', 4326));
COMMIT;
```

After executing the INSERT statement, we can verify that all geometries are valid ones, see Listing 5.

LISTING 5. Validation of the geometries from the table cities

```
SELECT c.id, ST_IsValid(c.location)
FROM cities c
ORDER BY c.id ASC;

+----+------------------------+
| id | ST_IsValid(c.location) |
+----+------------------------+
|  1 |                      1 |
|  2 |                      1 |
|  3 |                      1 |
|  4 |                      1 |
|  5 |                      1 |
|  6 |                      1 |
|  7 |                      1 |
|  8 |                      1 |
|  9 |                      1 |
| 10 |                      1 |
+----+------------------------+
10 rows in set (0.00 sec)
```

We can also check the metadata connected with this geometry layer, see Listing 6. This metadata was completed automatically by the system.

Listing 6. Checking the metadata for the table cities

```
SELECT *
FROM INFORMATION_SCHEMA.ST_GEOMETRY_COLUMNS
WHERE TABLE_NAME='cities';

+----------+---------+--------+---------+-------+------+--------------+
|TABLE_CATALOG |TABLE_SCHEMA |TABLE_NAME |COLUMN_NAME  |SRS_NAME  |SRS_ID |GEOMETRY_TYPE_NAME |
+----------+---------+--------+---------+-------+------+--------------+
| def      | examples | cities | location | WGS 84| 4326 | geometry     |
+----------+---------+--------+---------+-------+------+--------------+
1 row in set (0.00 sec)
```

Now let us display the names of the cities, their population, appropriate WKT representations of their locations (using `ST_AsText` conversion function) and latitude and longitude values related to these geometries (let us notice that in WKT representation in MySQL the latitude is given first by default). The results of the query are ordered in descending order by population size, see Listing 7.

Listing 7. Displaying the WKT representation of geometries from the table cities along with latitude and longitude values related to their location

```
SELECT c.name NAME, c.population POPULATION, ST_AsText(c.location) WKT,
      ST_Latitude(c.location) LATITUDE, ST_Longitude(c.location) LONGITUDE
FROM cities c
ORDER BY c.population DESC;

+-----------+------------+--------------------+----------+-----------+
| NAME      | POPULATION | WKT                | LATITUDE | LONGITUDE |
+-----------+------------+--------------------+----------+-----------+
| Warszawa  |    1860281 | POINT(52.12 21.02) |    52.12 |     21.02 |
| Kraków    |     800653 | POINT(50.03 19.57) |    50.03 |     19.57 |
| Wrocław   |     672929 | POINT(51.07 17.02) |    51.07 |     17.02 |
| Łódź      |     670642 | POINT(51.47 19.28) |    51.47 |     19.28 |
| Poznań    |     546859 | POINT(52.25 16.55) |    52.25 |     16.55 |
| Gdańsk    |     486022 | POINT(54.22 18.38) |    54.22 |     18.38 |
| Szczecin  |     396168 | POINT(53.26 14.34) |    53.26 |     14.34 |
| Bydgoszcz |     337666 | POINT(53.07 18)    |    53.07 |        18 |
| Lublin    |     334681 | POINT(51.14 22.34) |    51.14 |     22.34 |
| Białystok |     294242 | POINT(53.08 23.1)  |    53.08 |      23.1 |
+-----------+------------+--------------------+----------+-----------+
10 rows in set (0.00 sec)
```

In Listing 8, let us display the names of the three cities with the largest population together with the GeoJSON representation of their locations.

Listing 8. Displaying the GeoJSON representation of the locations of the three cities with the largest population

```
SELECT c.name NAME, ST_AsGeoJSON(c.location) GEOJSON
FROM cities c
ORDER BY c.population DESC
LIMIT 3;

+----------+-----------------------------------------------+
| NAME     | GEOJSON                                       |
+----------+-----------------------------------------------+
| Warszawa | {"type": "Point", "coordinates": [21.02, 52.12]} ||
  Kraków   | {"type": "Point", "coordinates": [19.57, 50.03]} ||
  Wrocław  |  {"type":  "Point",  "coordinates":  [17.02    51.07]}  |
+----------+-----------------------------------------------+
3 rows in set (0.00 sec)
```

By using `ST_AsBinary` function, let us find the WKB representation of the city of Warszawa (Warsaw – the capital of Poland) (see Listing 9), and using `ST_GeoHash` function (along with `ST_Longitude` and `ST_Latitude` functions) – the names and a geohash values for the cities with the population greater then 1 000 000 (see

Listing 10). Checking this geohash value in any website converter, for instance in [63], we actually will result in a location in the capital of Poland.

Listing 9. Displaying the WKB representation of the city of Warszawa

```
SELECT ST_AsBinary(c.location) WKB
FROM cities c
WHERE c.name='Warszawa';

+----------------------------------------------+
| WKB                                          |
+----------------------------------------------+
| 0x01010000008FC2F5285C0F4A4085EB51B81E053540 |
+----------------------------------------------+
1 row in set (0.00 sec)
```

Listing 10. Displaying the geohash value for the locations of cities with population over 1 000 000

```
SELECT c.name NAME,
ST_GeoHash(ST_Longitude(c.location), ST_Latitude(c.location), 20) GeoHash
FROM cities c
WHERE c.population>1000000;

+----------+----------------------+
| NAME     | GeoHash              |
+----------+----------------------+
| Warszawa | u3qbw24m180n27ys6p1h |
+----------+----------------------+
1 row in set (0.00 sec)
```

Now let us create a user EXAMPLES (with CONNECT and RESOURCE roles) in pluggable database XEPDB1 in Oracle Database 21c Express Edition Release 21.0.0.0.0 - Production Version 21.3.0.0.0 (using the SYSTEM account in XEPDB1) and let us connect to this schema from SQL* Plus (see Listing 11).

Listing 11. Creating the EXAMPLE user

```
conn system@XEPDB1

CREATE USER "EXAMPLES" IDENTIFIED BY "examples"
DEFAULT TABLESPACE "USERS"
TEMPORARY TABLESPACE "TEMP";
ALTER USER "EXAMPLES" QUOTA 20M ON "USERS";
GRANT "CONNECT", "RESOURCE" TO "EXAMPLES" ;

conn EXAMPLES@XEPDB1
```

Let us create an analogous table CITIES in this schema, using native Oracle SDO_GEOMETRY type (and without auto-incrementation, that is, without Identity Column), see Listing 12.

Listing 12. Creating the CITIES table in Oracle

```
CREATE TABLE cities(
id NUMBER CONSTRAINT cities_PK PRIMARY KEY,
name VARCHAR2(50 CHAR) NOT NULL,
population NUMBER NOT NULL,
location SDO_GEOMETRY NOT NULL
);
```

To import the data from MySQL DBMS to Oracle XE database, let us execute in MySQL a properly prepared query which gives as a result the appropriate insert statements that can later be used in Oracle, see Listing 13. This query takes advantage of MySQL `CONCAT` function that concatenates given texts, MySQL `ST_AsText` function that returns a WKT representation of a given geometry and an Oracle constructor of a SDO_GEOMETRY type taking a WKT and a SRID as input arguments. Let us notice that this export-import idea can be used thanks to the WKT representation and thanks to an optional argument of `ST_AsText` function in MySQL that allows to establish axis order in that representation. For in Oracle's version of the WKT representation longitude goes first, before latitude, which makes it impossible to just take a copy of a default WKT representation from MySQL.

LISTING 13. Creating the insert statements to enable the export of data from MySQL to Oracle XE (using ST_AsText function)

```
-- in EXAMPLES database in MYSQL DBMS:

SELECT CONCAT(
   "INSERT INTO cities VALUES(", c.id,",'",c.name,"',",c.population, ",
    SDO_GEOMETRY('", ST_AsText(c.location, 'axis-order=long-lat'),"',
     4326));") TEXT
FROM cities c;

+----------------------------------------------------------------+
| TEXT                                                           |
+----------------------------------------------------------------+
| INSERT INTO cities VALUES
  (1,'Warszawa',1860281,SDO_GEOMETRY('POINT(21.02 52.12)', 4326)); |
| INSERT INTO cities VALUES
  (2,'Kraków',800653,SDO_GEOMETRY('POINT(19.57 50.03)', 4326));    ||
  INSERT INTO cities VALUES
  (3,'Wrocław',672929,SDO_GEOMETRY('POINT(17.02  51.07)',  4326));  |
|  INSERT  INTO  cities  VALUES
  (4,'Łódź',670642,SDO_GEOMETRY('POINT(19.28 51.47)',4326));        |
|  INSERT  INTO  cities  VALUES
  (5,'Poznań',546859,SDO_GEOMETRY('POINT(16.55  52.25)',  4326));   |
|  INSERT  INTO  cities  VALUES
  (6,'Gdańsk',486022,SDO_GEOMETRY('POINT(18.38  54.22)',  4326));   |
|  INSERT  INTO  cities  VALUES
  (7,'Szczecin',396168,SDO_GEOMETRY('POINT(14.34 53.26)', 4326));  |
| INSERT INTO cities VALUES
  (8,'Bydgoszcz',337666,SDO_GEOMETRY('POINT(18 53.07)', 4326));    |
| INSERT INTO cities VALUES
  (9,'Lublin',334681,SDO_GEOMETRY('POINT(22.34 51.14)', 4326));    |
| INSERT INTO cities VALUES
  (10,'Białystok',294242,SDO_GEOMETRY('POINT(23.1 53.08)', 4326)); |
+----------------------------------------------------------------+
10 rows in set (0.00 sec)
```

By executing obtained insert statements on an EXAMPLE user account, we populate the table CITIES with appropriate data. We can easily check that the geometries created this way are valid (see Listing 14).

LISTING 14. Validation of the geometries from the table CITIES

```
SELECT c.id, c.location.ST_IsValid()
FROM cities c
ORDER BY c.id ASC;

        ID C.LOCATION.ST_ISVALID()
---------- ----------------------
         1                      1
         2                      1
         3                      1
         4                      1
         5                      1
         6                      1
         7                      1
         8                      1
         9                      1
        10                      1
10 rows selected.
```

In Oracle Spatial and Graph 21c, we have to take care of introducing the metadata on our own executing an appropriate insert statement to USER_SDO_GEOM_METADATA view, see Listing 15 (0.5 stands there for a tolerance value for each of the dimensions).

LISTING 15. Inserting the metadata for the table CITIES

```
INSERT INTO user_sdo_geom_metadata VALUES (
'CITIES',
'LOCATION',
```

```
SDO_DIM_ARRAY(
SDO_DIM_ELEMENT('longitude',-180,180,0.5),
SDO_DIM_ELEMENT('latitude',-90,90,0.5)
),
4326
);
COMMIT;
```

Asking the database to display the content of the table CITIES, we are able to see the native version of Oracle's constructor of a SDO_GEOMETRY type, see Listing 16.

Listing 16. The contents of table CITIES in Oracle XE database (with native constructors calls)

```
SET PAGESIZE 50
SELECT * FROM cities c ORDER BY c.population DESC;

ID NAME     POPULATION  LOCATION(SDO_GTYPE,SDO_SRID,SDO_POINT(X,Y,Z),SDO_ELEM_INFO,SDO_ORDINATES)
- ------- -------- ---------------------------------------------------------
1 Warszawa 1860281 SDO_GEOMETRY(2001, 4326, SDO_POINT_TYPE(21.02, 52.12, NULL), NULL, NULL)
2 Kraków    800653 SDO_GEOMETRY(2001, 4326, SDO_POINT_TYPE(19.57, 50.03, NULL), NULL, NULL)
3 Wrocław   672929 SDO_GEOMETRY(2001, 4326, SDO_POINT_TYPE(17.02, 51.07, NULL), NULL, NULL)
4 Łódź      670642 SDO_GEOMETRY(2001, 4326, SDO_POINT_TYPE(19.28, 51.47, NULL), NULL, NULL)
5 Poznań    546859 SDO_GEOMETRY(2001, 4326, SDO_POINT_TYPE(16.55, 52.25, NULL), NULL, NULL)
6 Gdańsk    486022 SDO_GEOMETRY(2001, 4326, SDO_POINT_TYPE(18.38, 54.22, NULL), NULL, NULL)
7 Szczecin  396168 SDO_GEOMETRY(2001, 4326, SDO_POINT_TYPE(14.34, 53.26, NULL), NULL, NULL)
8 Bydgoszcz  337666 SDO_GEOMETRY(2001, 4326, SDO_POINT_TYPE(18, 53.07, NULL), NULL, NULL)
9 Lublin     334681 SDO_GEOMETRY(2001, 4326, SDO_POINT_TYPE(22.34, 51.14, NULL), NULL, NULL)
10 Białystok 294242 SDO_GEOMETRY(2001, 4326, SDO_POINT_TYPE(23.1, 53.08, NULL), NULL, NULL)
10 rows selected.
```

To display the WKT and WKB representations of the cities (here for instance for the cities with names ending with the letter "w"), one can use `Get_WKT()` and `Get_WKB()` methods called on objects stored in LOCATION column or appropriate functions from SDO_UTIL package, see Listing 17.

Listing 17. The WKT and WKB representations of locations of the cities with names ending with letter "w"

```
SELECT c.name NAME, c.location.Get_WKT() WKT, c.location.Get_WKB() WKB
FROM cities c
WHERE SUBSTR(c.name,-1,1)='w'
ORDER BY c.population DESC;

SELECT c.name NAME, SDO_UTIL.TO_WKTGEOMETRY(c.location) WKT,
       SDO_UTIL.TO_WKBGEOMETRY(c.location) WKB
FROM cities c
WHERE SUBSTR(c.name,-1,1)='w'
ORDER BY c.population DESC;

NAME      WKT                   WKB
--------- -------------------- ----------------------------------------
Kraków    POINT  (19.57  50.03)  0000000001403391EB851EB852404903D70A3D70A4
Wrocław   POINT  (17.02  51.07)  00000000014031051EB851EB85404988F5C28F5C29
```

Similarly the GML and GeoJSON representation can be obtained (here for the city of Łódź), see Listing 18.

Listing 18. The GML and GeoJSON representations of location of the city of Łódź

```
SET LONG 40000

SELECT SDO_UTIL.TO_GMLGEOMETRY (c.location) GML_v2
FROM cities c
WHERE c.name='Łódź';

GML_V2
--------------------------------------------------------------------------
<gml:Point srsName="EPSG:4326" xmlns:gml="http://www.opengis.net/gml">
<gml:coordinates decimal="." cs="," ts=" ">19.28,51.47 </gml:coordinates>
</gml:Point>
```

```
SELECT SDO_UTIL.TO_GML311GEOMETRY (c.location) GML_v3
FROM cities c
WHERE c.name='Łódź';

GML_V3
--------------------------------------------------------------------------
<gml:Point srsName="EPSG:4326" xmlns:gml="http://www.opengis.net/gml">
<gml:pos srsDimension="2">19.28 51.47 </gml:pos></gml:Point>

SELECT SDO_UTIL.TO_GEOJSON(c.location) GEOJSON
FROM cities c
WHERE c.name='Łódź';

GEOJSON
--------------------------------------------------------------------------
{ "type": "Point", "coordinates": [19.28, 51.47] }
```

It is worth mentioning that in `Get_GML` method we can change the coordinates order in GML format, see Listing 19.

Listing 19. The GML representations of location of the city of Łódź with changed order of the coordinates

```
SELECT c.location.GET_GML() "GML long/lat",
       c.location.GET_GML(1) "GML lat/long"
FROM cities c
WHERE c.name='Łódź';

GML long/lat                              GML lat/long
----------------------------------------- ------------------------------
<gml:Point srsName="EPSG:4326"            <gml:Point srsName="EPSG:4326"
xmlns:gml=                                xmlns:gml=
"http://www.opengis.net/gml">             "http://www.opengis.net/gml">
<gml:coordinates decimal="."              <gml:coordinates decimal="."
cs="," ts=" ">19.28,51.47                 cs="," ts=" ">51.47,19.28
</gml:coordinates></gml:Point>            </gml:coordinates></gml:Point>
```

Let us also notice that the similar export-import idea as presented earlier could involve Oracle `SDO_UTIL.FROM_GEOJSON` function and MySQL `ST_AsGeoJSON` function (without any problems with coordination's order), see Listing 20. One could also involve `SDO_UTIL.FROM_WKTGEOMETRY` function (together with MySQL `ST_AsText` function, with the change of the coordinates order), but in that case we obtain geometries with NULL value as a SRID (as the WKT representation itself does not contain the information about the coordinate system used), so after the execution of insert statement in Oracle XE, it is necessary to update all imported rows setting SDO_SRID field value to the appropriate coordinate system identifier, see Listing 21.

Listing 20. Creating the insert statements to enable the export of data from MySQL to Oracle XE (using `SDO_UTIL.FROM_GEOJSON` function)

```
-- in EXAMPLES database in MYSQL DBMS:

SELECT CONCAT("INSERT INTO cities VALUES(", c.id,",'",c.name,"',",c.population, ",  SDO_UTIL.
    FROM_GEOJSON('", ST_AsGeoJSON(c.location), "', NULL, 4326));") TEXT
FROM cities c;

+------------------------------------------------------------------------+
| TEXT                                                                   |
+------------------------------------------------------------------------+
| INSERT INTO cities VALUES(1,'Warszawa',1860281,
  SDO_UTIL.FROM_GEOJSON
('{"type": "Point", "coordinates": [21.02, 52.12]}',  NULL, 4326));    ||
INSERT INTO cities VALUES(2,'Kraków',800653,
  SDO_UTIL.FROM_GEOJSON
  ('{"type": "Point", "coordinates": [19.57, 50.03]}',  NULL, 4326));    |
...
+------------------------------------------------------------------------+
10 rows in set (0.00 sec)
```

Listing 21. Creating the insert statements to enable the export of data from MySQL to Oracle XE (using SDO_UTIL.FROM_WKTGEOMETRY function and updating a SRID identifier after import)

```
-- in EXAMPLES database in MYSQL DBMS:

SELECT CONCAT("INSERT INTO cities VALUES(", c.id,",'",c.name,"',",c.population, ",SDO_UTIL.
    FROM_WKTGEOMETRY('", ST_AsText(c.location,  'axis-order=long-lat'),"'));") TEXT
FROM cities c;

+----------------------------------------------------------------------+
| TEXT                                                                 |
+----------------------------------------------------------------------+
| INSERT INTO cities VALUES(1,'Warszawa',1860281,
  SDO_UTIL.FROM_WKTGEOMETRY('POINT(21.02 52.12)')); |                  |
  INSERT INTO cities VALUES(2,'Kraków',800653,
  SDO_UTIL.FROM_WKTGEOMETRY('POINT(19.57 50.03)'));                    |
...

+----------------------------------------------------------------------+
10 rows in set (0.00 sec)

-- in Oracle XE database, after insert statements:

UPDATE cities c
SET c.location.SDO_SRID=4326;
COMMIT;
```

Summarizing these export-import ideas, it can be seen that in the case of these two systems, using the GeoJSON representation seems to be the most elegant and the least troublesome.

In Oracle database, we can also export geometries to JSON, KML and GeoHash, see Listing 22.

Listing 22. JSON, KML and GeoHash representations of locations of chosen cities

```
SELECT c.name NAME, SDO_UTIL.TO_JSON_JSON(c.location) JSON
FROM cities c
WHERE c.population BETWEEN 500000 AND 600000
ORDER BY c.population DESC;

NAME     JSON
-------- -------------------------------------------------------------
Poznań   {"srid":4326,"point":{"directposition":[16.55,52.25]}}

SELECT c.name NAME, SDO_UTIL.TO_KMLGEOMETRY(c.location) KML
FROM cities c
WHERE c.name LIKE 'By%';

NAME        KML
----------- ----------------------------------------------------------
Bydgoszcz   <Point><extrude>0</extrude><tessellate>0</tessellate>
            <altitudeMode>relativeToGround</altitudeMode>
            <coordinates>18.0,53.07 </coordinates></Point>

SELECT c.name NAME, SDO_CS.TO_GEOHASH(c.location, 15) GEOHASH
FROM cities c
WHERE c.name LIKE 'K%';

NAME      GEOHASH
-------- ----------------------------------------------------------
Kraków    u2vut7dmy5cwszc
```

We also have the ability to validate WKT or WKB representations (with OGC definitions), see Listing 23 with WKT validation.

Listing 23. Validation of a chosen WKT representation

```
SELECT SDO_UTIL.VALIDATE_WKTGEOMETRY('POINT(21.02 52.12)') VALIDATION
FROM DUAL;
```

```
VALIDATION
--------------------------------------------------------------------------
TRUE
```

Listing 24 demonstrates how to invoke sample functions or methods for elements of ST_GEOMETRY type. To obtain elements of this type we cast values of LOCATION column of the CITIES table to ST_GEOMETRY.

Listing 24. The chosen functions and methods invoked for ST_GEOMETRY objects

```
SELECT ST_GEOMETRY(c.location).GET_WKT() WKT
FROM cities c
WHERE c.name='Lublin';

WKT
--------------------------------------------------------------------------
POINT (22.34 51.14)

SELECT ST_GEOMETRY.ST_ASTEXT(ST_GEOMETRY(c.location)) WKT
FROM cities c
WHERE c.name='Poznań';

WKT
--------------------------------------------------------------------------
POINT (16.55 52.25)

SELECT mdsys.ogc_ASTEXT(ST_GEOMETRY(c.location)) WKT
FROM cities c
WHERE c.name='Gdańsk';

WKT
--------------------------------------------------------------------------
POINT (18.38 54.22)
```

Let us now move (using default postgresql user) to the database postgis_34_sample in PostgreSQL 14 with PostGIS version 3.4.1 and create there the table cities by executing via SQL Shell (psql) a statement shown in Listing 25. Let us notice that in practice, when creating such a table, we probably would assign the location column not the geometry type but the geography type. In this paper, we have chosen geometry to be able to show how certain functions work.

Listing 25. Creating the cities table in PostgreSQL/ PostGIS

```
CREATE TABLE cities(
id SERIAL CONSTRAINT cities_PK PRIMARY KEY,
name VARCHAR(50) NOT NULL,
population INT NOT NULL,
location GEOMETRY(POINT, 4326));
```

The appropriate layer metadata in PostGIS are filled automatically; it can be checked by executing the query from Listing 26.

Listing 26. Checking the metadata for the table cities

```
SELECT *
FROM GEOMETRY_COLUMNS
WHERE f_table_name='cities';

f_table_catalog  |f_table_schema|f_table_name|f_geometry_column|coord_dimension| srid | type
-------------+----------+---------+-------------+-----------+-----+----
postgis_34_sample| public       | cities     | location       |            2 | 4326 | POINT
(1 row)
```

In PostGIS, as in Oracle, in the WKT representation the longitude goes first. Let us come back to the Oracle database again, and prepare and execute there a query that enables export of data to the postgis_34_sample database, see Listing 27. That query uses an Oracle concatenation operator ||, the possibility to access the coordinates of a point through the fields of the SDO_POINT object (which is a field of SDO_GEOMETRY object), and `ST_PointFromText` function in PostGIS module.

Listing 27. Creating the insert statements to enable the export of data from Oracle XE to postgis_34_sample database (using ST_PointFromText function)

```
-- in Oracle XE database:

SELECT 'INSERT INTO cities  VALUES(' || c.id ||  ', ''' || c.name ||''', ' || c.population || ',
    ST_PointFromText(''POINT(' || c.location.sdo_point.x || ' ' ||  c.location.sdo_point.y || ')''
    ,4326));' TEXT
FROM cities c;

TEXT
------------------------------------------------------------------------
INSERT INTO cities  VALUES(1, 'Warszawa', 1860281, ST_PointFromText('POINT(21.02 52.12)',4326));
INSERT INTO cities  VALUES(2, 'Kraków', 800653, ST_PointFromText('POINT(19.57 50.03)',4326));
INSERT INTO cities  VALUES(3, 'Wrocław',672929,ST_PointFromText('POINT(17.02 51.07)',4326));
INSERT INTO cities  VALUES(4, 'Łódź',670642,ST_PointFromText('POINT(19.28 51.47)',4326));
INSERT INTO cities  VALUES(5, 'Poznań', 546859, ST_PointFromText('POINT(16.55 52.25)',4326));
INSERT INTO cities  VALUES(6, 'Gdańsk', 486022, ST_PointFromText('POINT(18.38 54.22)',4326));
INSERT INTO cities  VALUES(7, 'Szczecin', 396168, ST_PointFromText('POINT(14.34 53.26)',4326));
INSERT INTO cities  VALUES(8, 'Bydgoszcz', 337666, ST_PointFromText('POINT(18 53.07)',4326));
INSERT INTO cities  VALUES(9, 'Lublin', 334681, ST_PointFromText('POINT(22.34 51.14)',4326));
INSERT INTO cities  VALUES(10, 'Białystok', 294242, ST_PointFromText('POINT(23.1 53.08)',4326));
10 rows selected.
```

Let us change the client encoding in SQL Shell to WIN1251 (to solve the problem with Polish diacritics) by executing the command presented in Listing 28.

Listing 28. Encoding change

```
SET client_encoding = 'WIN1251';
```

Now the insert statements obtained in Oracle can be executed in postgis_34_sample database. After the import we can check that all geometries are valid ones, see Listing 29.

Listing 29. Validation of the geometries from the table cities

```
SELECT c.id, ST_IsValid(c.location) FROM cities c ORDER BY c.id;

 id | st_isvalid
----+------------
  1 | t
  2 | t
  3 | t
  4 | t
  5 | t
  6 | t
  7 | t
  8 | t
  9 | t
 10 | t
(10 rows)
```

Let us now choose the cities that are within 200 kilometres from city of Warszawa, and display their names, along with their WKT and EWKT representations, see Listing 30. Let us notice that before filtering the cities located within some distance from the capital of Poland, we cast the geometry type to geography.

Listing 30. Selecting cities located within 200 kilometres of the city of Warszawa

```
SELECT c.name "NAME", ST_AsText(c.location) "WKT",
       ST_AsEWKT(c.location) "EWKT"
FROM cities c
WHERE ST_DWithin(c.location:: geography, (SELECT d.location
                                          FROM CITIES d
                                          WHERE d.name='Warszawa')::geography, 200000)
ORDER BY c.id;

   NAME    |        WKT         |             EWKT
-----------+--------------------+------------------------------
 Warszawa  | POINT(21.02 52.12) | SRID=4326;POINT(21.02 52.12)
```

```
 Łódź      | POINT(19.28 51.47) | SRID=4326;POINT(19.28 51.47)
 Lublin    | POINT(22.34 51.14) | SRID=4326;POINT(22.34 51.14)
 Białystok | POINT(23.1 53.08)  | SRID=4326;POINT(23.1 53.08)
(4 rows)
```

We can also covert the geometries to WKB, EWKB, HEXEWKB, TWKB formats, see Listing 31, and to GML, GeoJSON, GeoHash, KML and SVG, see Listing 32, or just put many functions together, see Listing 33.

Listing 31. Displaying the WKB, EWKB, HEXEWKB and TWKB representations of the locations of the selected cities

```
SELECT ST_AsBinary(c.location) "WKB", ST_AsTWKB(c.location) "TWKB"
FROM cities c
WHERE c.id=5;

                    WKB                       |          TWKB
----------------------------------------------+------------------------
 \x0101000000cdcccccccc8c3040000000000000204a40 | \xa100b083ca01d0e8fd04
(1 row)

SELECT ST_AsEWKB(c.location) "EWKB"
FROM cities c
WHERE c.id=5;

                        EWKB
------------------------------------------------------
 \x0101000020e6100000cdcccccccc8c3040000000000000204a40
(1 row)

SELECT c.name "NAME", ST_AsHEXEWKB(c.location) "HEXEWKB"
FROM cities c
WHERE c.name LIKE '_r%';

  NAME   |                       HEXEWKB ---------
+-------------------------------------------------Kraków   |
0101000020E610000052B81E85EB913340A4703D0AD7034940
 Wrocław | 0101000020E610000085EB51B81E053140295C8FC2F5884940 (2 rows)
```

Listing 32. Displaying the GML, GeoJSON, GeoHash, KML and SVG representations of the location of the city of Łódź

```
SELECT ST_AsGML(c.location) "GML"
FROM cities c
WHERE c.name='Łódź';
                                  GML
--------------------------------------------------------------------------
 <gml:Point srsName="EPSG:4326"><gml:coordinates>19.28,51.47</gml:coordinates>
 </gml:Point>
(1 row)

SELECT ST_AsGeoJSON(c.location) "GeoJSON",
       ST_GeoHash(c.location) "GeoHash"
FROM cities c
WHERE c.name='Łódź';

                   GeoJSON                    |       GeoHash
----------------------------------------------+----------------------
 {"type":"Point","coordinates":[19.28,51.47]} | u3jsy9z62x3vr6bkdewj
(1 row)

SELECT ST_AsKML(c.location) "KML", ST_AsSVG(c.location) "SVG"
FROM cities c
WHERE c.name='Łódź';


                   KML                   |           SVG
-----------------------------------------+---------------------------
```

```
 <Point><coordinates>19.28,51.47        | cx="19.28" cy="-51.47"
 </coordinates></Point>
(1 row)
```

Listing 33. Displaying the WKT representation of the union of geometries representing two selected cities (with additional use of functions converting geometry to and from WKB representation)

```
SELECT ST_AsText(
       ST_MPointFromWKB(ST_AsBinary(ST_UNION(c.location)))) "MULTIPOINT"
FROM cities c
WHERE c.id IN (1,2);

              MULTIPOINT
---------------------------------------
 MULTIPOINT((19.57 50.03),(21.02 52.12))
(1 row)
```

## 5. Conclusion

Spatial relation and object-relational database management systems use various formats to represent the geometric objects: both those defined and required by the main international standards (such as WKT, WKB and GML formats), those originally built for some application and then adopted as an international standard (such as KML format), those that are not maintained by any standards organization (such as GeoJSON) and those based on some algorithmic ideas (as Geohash). Some of the systems also propose and use their own extensions of such formats (e.g. PostGIS/PostgreSQL with EWKT and EWKB formats). Implementing functions and methods to support the handling of these formats through different relational and object-relational systems definitely facilitates work in these systems and the export and import of the spatial data. The birth of new lightweight formats used widely in the NoSQL databases (such as JSON/GeoJSON) forced the traditional database management systems to adopt these formats which expanded the capabilities of these systems and gives hope for some interoperability between traditional and new types of spatial databases management systems.

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**Data availability** The data used and analyzed in the paper is openly available on websites:

- Współrzędne geograficzne polskich miast (Geographic coordinates of Polish cities), https://astronomia.zagan.pl/art/wspolrzedne.html, author: Patka, J.
- Informacja o wynikach Narodowego Spisu Powszechnego Ludności i Mieszkań 2021 na poziomie województw, powiatów i gmin (Information on the results of the National of Population and Housing Census 2021 at the level voivodeships, poviats and communes), https://stat.gov.pl/download/gfx/portalinformacyjny/pl/defaultaktualnosci/6536/1/1/1/informacja_o_wynikach_narodowego_spisu_powszechnego_ludnosci_i_mieszkan_2021.pdf, Główny Urząd Statystyczny (Statistics Poland).

## References

[1] GeoJSON. https://geojson.org/, 2019. Last Accessed May 7, 2024.
[2] Introducing JSON. https://www.json.org/json-en.html, 2024. Last Accessed May 7, 2024.
[3] S. Agarwal and K. Rajan. Performance analysis of MongoDB versus PostGIS/PostGreSQL databases for line intersection and point containment spatial queries. *Spatial Information Research*, 24:671–677, 2016.
[4] S. Agarwal and K. Rajan. Analyzing the performance of NoSQL vs. SQL databases for Spatial and Aggregate queries. In *Free and Open Source Software for Geospatial (FOSS4G) Conference Proceedings*, volume 17, 2017. Available from: https://scholarworks.umass.edu/foss4g/vol17/iss1/4.
[5] P. Amirian, A. C. Winstanley, and A. Basiri. NoSQL storage and management of geospatial data with emphasis on serving geospatial data using standard geospatial web services. In *GIS Research UK (GISRUK) 2013*, pages 1–5, 2013. Available from: https://mural.maynoothuniversity.ie/6473/.
[6] C. Baptista, O. Junior, M. Oliveira, F. Andrade, T. Silva, and C. S. Pires. Using OGC services to interoperate spatial data stored in SQL and NoSQL databases. pages 61–72, 2011.

[7] E. Baralis, A. D. Valle, P. Garza, C. Rossi, and F. Scullino. SQL versus NoSQL databases for geospatial applications. In *2017 IEEE International Conference on Big Data (Big Data)*, pages 3388–3397, 2017. Available from: https://www.researchgate.net/publication/322516902_SQL_versus_NoSQL_databases_for_geospatial_applications, https://ieeexplore.ieee.org/document/8258324.

[8] D. Bartoszewski, A. Piórkowski, and M. Lupa. The Comparison of Processing Efficiency of Spatial Data for PostGIS and MongoDB Databases. In S. Kozielski, D. Mrozek, P. Kasprowski, B. Małysiak-Mrozek, and D. Kostrzewa, editors, *Beyond Databases, Architectures and Structures. Paving the Road to Smart Data Processing and Analysis*, pages 291–302, Cham, 2019. Springer International Publishing.

[9] Butler, H. and Daly, M. and Doyle, A. and Gillies, S. and Hagen, S. and Schaub, T. RFC 7946: The GeoJSON Format. https://www.rfc-editor.org/rfc/rfc7946, 2016. Last Accessed May 7, 2024.

[10] Cover Pages. Geography Markup Language (GML). http://xml.coverpages.org/geographyML.html, 2008. Last Accessed May 7, 2024.

[11] DataStax. Indexing and querying polygons | CQL for DataStax Enterprise | DataStax Docs. https://docs.datastax.com/en/cql/dse/cycling-examples/demoGeo.html, 2024. Last Accessed May 7, 2024.

[12] Ecma International. ECMA-404, The JSON data interchange syntax, 2nd edition, December 2017. https://www.ecma-international.org/publications-and-standards/standards/ecma-404/, 2017. Last Accessed May 7, 2024.

[13] W. B. Filho, H. V. Olivera, M. Holanda, and A. A. Favacho. Geographic Data Modeling for NoSQL Document-Oriented Databases. In *The Seventh International Conference on Advanced Geographic Information Systems, Applications, and Services, Lisboa, 2015*, pages 63–68, 2015. Available from: https://personales.upv.es/thinkmind/dl/conferences/geoprocessing/geoprocessing_2015/geoprocessing_2015_4_10_30113.pdf.

[14] Geographic Information Systems Stack Exchange. WKT coordinate inner order (long, lat). https://gis.stackexchange.com/questions/366853/wkt-coordinate-inner-order-long-lat, 2022. Last Accessed May 7, 2024.

[15] GitHub. TopoJSON. https://github.com/topojson/topojson/wiki, 2016. Last Accessed May 7, 2024.

[16] Główny Urząd Statystyczny (Statistics Poland). Informacja o wynikach Narodowego Spisu Powszechnego Ludności i Mieszkań 2021 na poziomie województw, powiatów i gmin (Information on the results of the National of Population and Housing Census 2021 at the level voivodeships, poviats and communes). https://stat.gov.pl/download/gfx/portalinformacyjny/pl/defaultaktualnosci/6536/1/1/1/informacja_o_wynikach_narodowego_spisu_powszechnego_ludnosci_i_mieszkan_2021.pdf, Sep 2022. Last Accessed July 4, 2023.

[17] Google Developers. Google Developers, Google Maps Platform: Encoded Polyline Algorithm Format. https://developers.google.com/maps/documentation/utilities/polylinealgorithm?hl=en, 2024. Last Accessed May 7, 2024.

[18] D. Guo and E. Onstein. State-of-the-Art Geospatial Information Processing in NoSQL Databases. *ISPRS International Journal of Geo-Information*, 9(5):331, 2020. Available from: https://www.mdpi.com/2220-9964/9/5/331/pdf?version=1590501181.

[19] J. A. Herrera-Ramírez, M. Treviño-Villalobos, and L. Víquez-Acuña. Hybrid storage engine for geospatial data using NoSQL and SQL paradigms. *Revista Tecnología en Marcha*, 34:40–54, 2021. Available from: http://www.scielo.sa.cr/scielo.php?script=sci_arttext&pid=S0379-39822021000100040&nrm=iso.

[20] ISO. ISO/IEC 2382-1:1993, Information technology - Vocabulary - Part 1: Fundamental terms. https://www.iso.org/standard/7229.html, 1993. Last Accessed May 7, 2024.

[21] ISO. ISO 19125-1:2004, Geographic information - Simple feature access - Part 1: Common architecture. https://www.iso.org/standard/40114.html, 2004. Last Accessed May 7, 2024.

[22] ISO. ISO 19125-2:2004, Geographic information - Simple feature access - Part 2: SQL option. https://www.iso.org/standard/40115.html, 2004. Last Accessed May 7, 2024.

[23] ISO. ISO 19136:2007, Geographic information - Geography Markup Language (GML). https://www.iso.org/standard/32554.html, 2007. Last Accessed May 7, 2024.

[24] ISO. ISO/IEC 13249-3:2016 Information technology - Database languages - SQL multimedia and application packages - Part 3: Spatial. https://www.iso.org/standard/60343.html, 2016. Last Accessed May 7, 2024.

[25] ISO. ISO 19136-1:2020, Geographic information - Geography Markup Language (GML) - Part 1: Fundamentals. https://www.iso.org/standard/75676.html, 2020. Last Accessed May 7, 2024.

[26] Krishnan, A. Hackr.io: JSON vs XML in 2024: Comparing Features and Examples. https://hackr.io/blog/json-vs-xml, 2024. Last Accessed May 7, 2024.

[27] D. Laksono. Testing Spatial Data Deliverance in SQL and NoSQL Database Using NodeJS Fullstack Web App. In *2018 4th International Conference on Science and Technology (ICST)*, pages 1–5, 2018.

[28] Y. Li, D. Kim, and B.-S. Shin. Geohashed Spatial Index Method for a Location-Aware WBAN Data Monitoring System Based on NoSQL. *Journal of Information Processing Systems*, 12(2):263–274, 2016. Available from: https://koreascience.kr/article/JAKO201621650894684.pdf.

[29] C.-T. Lu, R. F. D. S. Jr, L. N. Sripada, and Y. Kou. Advances in GML for Geospatial Applications. *Geoinformatica*, 11:131–157, 2007.

[30] Open Geospatial Consortium. OpenGIS Simple Features Implementation Specification for SQL, 1.1, 99-049. https://portal.ogc.org/files/?artifact_id=829, May 1999. Last Accessed May 7, 2024.

[31] Open Geospatial Consortium. OpenGIS Implementation Specification for Geographic information - Simple feature access - Part 1: Common architecture, 1.1.0, 05-126. https://portal.ogc.org/files/?artifact_id=13227, Nov 2005. Last Accessed May 7, 2024.

[32] Open Geospatial Consortium. OpenGIS Implementation Specification for Geographic information - Simple feature access - Part 2: SQL option, 1.1.0, 05-134. https://portal.ogc.org/files/?artifact_id=13228, Nov 2005. Last Accessed May 7, 2024.

[33] Open Geospatial Consortium. OpenGIS Implementation Specification for Geographic information - Simple feature access - Part 1: Common architecture, 1.2.0, 06-103r3. https://portal.ogc.org/files/?artifact_id=18241, Oct 2006. Last Accessed May 7, 2024.

[34] Open Geospatial Consortium. OpenGIS Implementation Specification for Geographic information - Simple feature access - Part 2: SQL option, 1.2.0, 06-104r3. https://portal.ogc.org/files/?artifact_id=18242, Oct 2006. Last Accessed May 7, 2024.

[35] Open Geospatial Consortium. OpenGIS Implementation Specification for Geographic information - Simple feature access - Part 2: SQL option, 1.2.1, 06-104r4. https://portal.ogc.org/files/?artifact_id=25354, Aug 2010. Last Accessed May 7, 2024.

[36] Open Geospatial Consortium. OpenGIS Implementation Specification for Geographic information - Simple feature access - Part 1: Common architecture, 1.2.1, 06-103r4. https://portal.ogc.org/files/?artifact_id=25355, May 2011. Last Accessed May 7, 2024.

[37] Open Geospatial Consortium. Certified Product List (Product Provider: Crunchy Data). https://www.ogc.org/resources/certified-products/?display_opt=1&org_match=Crunchy%20Data, 2023. Last Accessed July 4, 2023.
[38] Open Geospatial Consortium. Certified Product List (Product Provider: Oracle USA). https://www.ogc.org/resources/certified-products/?display_opt=1&org_match=Oracle%20USA, 2023. Last Accessed July 4, 2023.
[39] Open Geospatial Consortium. Geography Markup Language. https://www.ogc.org/standards/gml, 2023. Last Accessed May 7, 2024.
[40] Open Geospatial Consortium. KML. https://www.ogc.org/standards/kml, 2023. Last Accessed May 7, 2024.
[41] Open Geospatial Consortium. Simple Feature Access - Part 1: Common Architecture. https://www.ogc.org/standards/sfa, 2023. Last Accessed May 7, 2024.
[42] Open Geospatial Consortium. Simple Feature Access - Part 2: SQL Option. https://www.ogc.org/standards/sfs, 2023. Last Accessed May 7, 2024.
[43] Oracle. Oracle Database Online Documentation 12c Release 1 (12.1) E41152-15, Application Development, XML DB Developer's Guide, 39.1.2: Overview of JSON Compared with XML. https://docs.oracle.com/database/121/ADXDB/json.htm#ADXDB6250, Dec 2016. Last Accessed July 4, 2023.
[44] Oracle. Spatial and Graph Analytics with Oracle Database 12c Release 2, ORACLE WHITEPAPER, NOVEMBER 2016. https://www.oracle.com/technetwork/database/options/spatialandgraph/spatial-and-graph-wp-12c-1896143.pdf, Nov 2016. Last Accessed May 7, 2024.
[45] Oracle. Spatial and Graph Analytics with Oracle Database 18, ORACLE WHITE PAPER, FEBRUARY 2018. https://download.oracle.com/otndocs/products/spatial/pdf/Spatial_and_Graph_TWP_18c.pdf, Feb 2018. Last Accessed May 7, 2024.
[46] Oracle. Oracle Spatial and Graph in Oracle Database 19c. https://www.oracle.com/a/tech/docs/spatial-and-graph-in-oracle-database-19c-preso.pdf, 2019. Last Accessed May 7, 2024.
[47] Oracle. MySQL 8.0 Reference Manual Including MySQL NDB Cluster 8.0, 2023-07-04, revision: 76058. https://downloads.mysql.com/docs/refman-8.0-en.a4.pdf, Jul 2023. Last Accessed July 4, 2023.
[48] Oracle. Oracle: Spatial and Graph features in Oracle Database. https://www.oracle.com/database/technologies/spatialandgraph.html, 2023. Last Accessed July 4, 2023.
[49] Oracle. Oracle ®Spatial Spatial Developer's Guide 21c F32277-17, July 2023. https://docs.oracle.com/en/database/oracle/oracle-database/21/spatl/spatial-developers-guide.pdf, Jul 2023. Last Accessed July 4, 2023.
[50] OSGeo. Axis Order Confusion. https://wiki.osgeo.org/wiki/Axis_Order_Confusion, 2018. Last Accessed May 7, 2024.
[51] Patka, J. Współrzędne geograficzne polskich miast (Geographic coordinates of Polish cities). https://astronomia.zagan.pl/art/wspolrzedne.html, 2008. Last Accessed May 7, 2024.
[52] PostGIS. PostGIS 2.2.1 Manual SVN Revision (14555). http://postgis.net/stuff/postgis-2.2.1.pdf, 2016. Last Accessed July 4, 2022.
[53] PostGIS. About PostGIS. https://postgis.net/, 2023. Last Accessed July 4, 2023.
[54] PostGIS. PostGIS 3.2.6dev Manual DEV (Thu 29 Jun 2023 04:28:52 AM UTC rev. 47ccf6a). https://postgis.net/stuff/postgis-3.2.pdf, Jun 2023. Last Accessed July 3, 2023.
[55] PostGIS. PostGIS 3.4.0dev Manual DEV (Wed 05 Jul 2023 08:34:57 AM UTC rev. 54f1530). https://postgis.net/stuff/postgis-3.4.pdf, Jul 2023. Last Accessed May 7, 2024.
[56] Ryeng, N. H. MySQL Blog Archive: Geography in MySQL 8.0. https://dev.mysql.com/blog-archive/geography-in-mysql-8-0/, 2018. Last Accessed May 7, 2024.
[57] Ryeng, N. H. MySQL Blog Archive: Upgrading to MySQL 8.0 with Spatial Data. https://dev.mysql.com/blog-archive/upgrading-to-mysql-8-0-with-spatial-data/, 2018. Last Accessed May 7, 2024.
[58] Safris, S. Toptal Engineering Blog: A Deep Look At JSON vs. XML, Part 2: The Strengths and Weaknesses of Both. https://www.toptal.com/web/json-vs-xml-part-2, 2019. Last Accessed May 7, 2024.
[59] P. O. Santos, M. M. Moro, and C. A. D. Jr. Comparative Performance Evaluation of Relational and NoSQL Databases for Spatial and Mobile Applications. In Q. Chen, A. Hameurlain, F. Toumani, R. Wagner, and H. Decker, editors, *Database and Expert Systems Applications*, pages 186–200, Cham, 2015. Springer International Publishing.
[60] solidIT consulting & software development gmbh. DB-Engines Ranking of Relational DBMS. https://db-engines.com/en/ranking/relational+dbms, 2024. Last Accessed May 7, 2024.
[61] I. S. Suwardi, D. Dharma, D. P. Satya, and D. P. Lestari. Geohash index based spatial data model for corporate. In *2015 International Conference on Electrical Engineering and Informatics (ICEEI)*, pages 478–483, 2015. Available from: https://ieeexplore.ieee.org/document/7352548.
[62] The PostgreSQL Global Development Group. The PostgreSQL Global Development Group, PostgreSQL 14.8 Documentation. https://www.postgresql.org/files/documentation/pdf/14/postgresql-14-A4.pdf, 2023. Last Accessed July 4, 2023.
[63] Veness, C. Movable Type Scripts, Geohashes: Geohash encoding/decoding. https://www.movable-type.co.uk/scripts/geohash.html, 2022. Last Accessed May 7, 2024.
[64] Whelan, P. Geohash Intro - Big Fast Blog. https://bigfastblog.com/geohash-intro, 2011. Last Accessed May 7, 2024.
[65] M. Wyszomirski. Przegląd możliwości zastosowania wybranych baz danych NoSQL do zarządzania danymi przestrzennymi (An overview of possibilities of using selected NoSQL databases to manage spatial data). *ROCZNIKI GEOMATYKI*, 16:55–69, 2018. Available from: http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-cc5a0a99-1da7-4fd9-8a87-3d7a8226ab27/c/5_Wyszomirski_Przeglad_55-69.pdf.
[66] X. Zhang, W. Song, and L. Liu. An implementation approach to store GIS spatial data on NoSQL database. In *22nd International Conference on Geoinformatics, 2014*, 2014.

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Table 1. Functions related to WKT and WKB formats described in SF standard - required functionality (based on [30])

| Format | Function Name | Input Arguments | Output |
|---|---|---|---|
| `WKT` | `AsText` | a geometry value as a Geometry (or any subtype of this type) | the WKT representation of the given geometry (as a String) |
| | `GeomFromText` | a WKT representation of a geometry (as a String) and a SRID (as an Integer) | the geometry value for that WKT representation (as a Geometry) |
| | `PointFromText`, `LineFromText`, `PolyFromText`, `MPointFromText`, `MLineFromText`, `MPolyFromText`, `GeomCollFromTxt` | a WKT representation of a geometry (as a String) and a SRID (as an Integer) | the geometry value of an appropriate type (respectively: Point, LineString, Polygon, MultiPoint, MultiLineString, MultiPolygon, GeometryCollection type) for that WKT representation |
| `WKB` | `AsBinary` | a geometry value as a Geometry (or any subtype of this type) | the WKB representation of the given geometry (as a Binary) |
| | `GeomFromWKB` | a WKB representation of a geometry (as Binary) and a SRID (as an Integer) | the geometry value for that WKB representation (as a Geometry) |
| | `PointFromWKB`, `LineFromWKB`, `PolyFromWKB`, `MPointFromWKB`, `MLineFromWKB`, `MPolyFromWKB`, `GeomCollFromWKB` | a WKB representation of a geometry (as a Binary) and a SRID (as an Integer) | the geometry value of an appropriate type (respectively: Point, LineString, Polygon, MultiPoint, MultiLineString, MultiPolygon, GeometryCollection type) for that WKB representation |

Table 2. Functions related to WKT and WKB formats described in SF standard - optional functionality (based on [30])

| Format | Function Name | Input Arguments | Output |
|---|---|---|---|
| `WKT` | `BdPolyFromText`, `BdMPolyFromText` | a WKT representation of a collection of closed linestrings (as a String with representation of MultiLineString) and a SRID (as an Integer) | a Polygon or MultiPolygon, respectively, for that WKT representation |
| `WKB` | `BdPolyFromWKB`, `BdMPolyFromWKB` | a WKB representation of a collection of closed linestrings (as a binary representation of MultiLineString) and a SRID (as an Integer) | a Polygon or MultiPolygon, respectively, for that WKB representation |

Table 3. Functions related to WKT and WKB formats provided by MySQL 8.0 (based on section 12.16 of [47])

| Format | Function Name | Input Arguments | Output |
|---|---|---|---|
| `WKT` | `ST_AsText` and `ST_AsWKT` | a geometry value in internal format, optionally an additional argument describing the axis order, in case of geographic coordinates | the WKT representation of the given geometry |
| | `ST_GeomFromText` and `ST_GeometryFromText` | a WKT representation of a geometry of any type, optionally a SRID, optionally a parameter describing the axis order, in case of geographic coordinates | the geometry value for that WKT representation |
| | `ST_PointFromText`, `ST_LineFromText` and `ST_LineStringFromText`, `ST_PolyFromText` and `ST_PolygonFromText`, `ST_MPointFromText` and `ST_MultiPointFromText`, `ST_MLineFromText` and `ST_MultiLineStringFromText`, `ST_MPolyFromText` and `ST_MultiPolygonFromText`, `ST_GeomCollFromText` and `ST_GeometryCollectionFromText` and `ST_GeomCollFromTxt` | a WKT representation of a geometry of an appropriate type, optionally a SRID, optionally a parameter describing the axis order, in case of geographic coordinates | the geometry value of the appropriate type (i.e. a Point, a LineString, a Polygon, a MultiPoint, a MultiLineString, a MultiPolygon, a GeometryCollection, respectively) for that WKT representation |
| `WKB` | `ST_AsBinary` and `ST_AsWKB` | a geometry value in internal format, optionally an additional argument describing the axis order, in case of geographic coordinates | the WKB representation of the given geometry |
| | `ST_GeomFromWKB` and `ST_GeometryFromWKB` | a BLOB with a WKB representation of a geometry of any type, optionally a SRID, optionally a parameter describing the axis order, in case of geographic coordinates | the geometry value for that WKB representation |
| | `ST_PointFromWKB`, `ST_LineFromWKB` and `ST_LineStringFromWKB`, `ST_PolyFromWKB` and `ST_PolygonFromWKB`, `ST_MPointFromWKB` and `ST_MultiPointFromWKB`, `ST_MLineFromWKB` and `ST_MultiLineStringFromWKB`, `ST_MPolyFromWKB` and `ST_MultiPolygonFromWKB`, `ST_GeomCollFromWKB` and `ST_GeometryCollectionFromWKB` | a WKB representation of a geometry of an appropriate type, optionally a SRID, optionally a parameter describing the axis order, in case of geographic coordinates | the geometry value of the appropriate type (i.e. a Point, a LineString, a Polygon, a MultiPoint, a MultiLineString, a MultiPolygon, a GeometryCollection, respectively) for that WKB representation |

Table 4. Functions related to GeoJSON and GeoHash formats in MySQL 8.0 (based on section 12.16 of [47])

| Format | Function Name | Input Arguments | Output |
|---|---|---|---|
| `GeoJSON` | `ST_AsGeoJSON` | a geometry value, optionally a maximal number of decimal digits for coordinates, and some optional parameter | the geometry value in a GeoJSON format |
| | `ST_GeomFromGeoJSON` | a string with a geometry in GeoJSON format and an optional parameter with some options and optionally a SRID | the geometry value for that GeoJSON representation (without support for Features and FeatureCollections, but with possibility to extract the geometry objects from them) |
| `GeoHash` | `ST_GeoHash` | longitude, latitude and a max_length parameter or a POINT value (with X and Y coordinates that are in the valid ranges for longitude and latitude, respectively) and max_length | the geohash string corresponding to the location indicated by longitude and latitude or by a POINT geometry (string no longer that a max_length characters) |
| | `ST_PointFromGeoHash` | a geohash string value and a SRID | the geometry value of a POINT type with coordinates indicating the longitude and the latitude of the location described by the given geohash value |
| | `ST_LatFromGeoHash`, `ST_LongFromGeoHash` | a geohash string value | the latitude (respectively: the longitude) of location described by a given geohash value (as a double-precision numbers) |

TABLE 5. Functions related to WKT, WKB and GML formats from SDO_UTIL package in Oracle XE 21c (based on [49])

| Format | Function Name | Input Arguments | Output |
|---|---|---|---|
| WKT | SDO_UTIL. TO_WKTGEOMETRY | a geometry value (as an SDO_GEOMETRY object) | the WKT representation for that geometry (as a CLOB) |
| | SDO_UTIL. FROM_WKTGEOMETRY | a WKT representation of a geometry (as a CLOB or as a VARCHAR2) | the geometry value for that WKT representation (as an SDO_GEOMETRY object) |
| WKB | SDO_UTIL. TO_WKBGEOMETRY | a geometry value (as an SDO_GEOMETRY object) | the WKB representation for that geometry (as a BLOB) |
| | SDO_UTIL. FROM_WKBGEOMETRY | a WKB representation of a geometry (as a BLOB) | the geometry value for that WKB representation (as an SDO_GEOMETRY object) |
| GML | SDO_UTIL. TO_GMLGEOMETRY | a geometry value (as an SDO_GEOMETRY object) or a geometry value and a coordOrder parameter (as a NUMBER, reserved for Oracle use) | the GML representation for that geometry (as a CLOB), with 2.0 version of GML |
| | SDO_UTIL. TO_GML311GEOMETRY | a geometry value (as an SDO_GEOMETRY object) | the GML representation for that geometry (as a CLOB), with 3.1.1 version of GML |
| | SDO_UTIL. FROM_GMLGEOMETRY | a geometry values in GML 2.0 version (as a CLOB or a VARCHAR2) and srsNamespace parameter (as a VARCHAR2, reserved for Oracle use, by default set to NULL) | the geometry value for that GML representation (as an SDO_GEOMETRY object) |
| | SDO_UTIL. FROM_GML311GEOMETRY | a geometry values in GML 3.1.1 version (as CLOB or as a VARCHAR2), srsNamespace (as a VARCHAR2) and / or coordOrder (as a NUMBER) | the geometry value for that GML representation (as an SDO_GEOMETRY object) |

Table 6. Functions related to GeoJSON / JSON and KML formats from SDO_UTIL package in Oracle XE 21c (based on [49])

| Format | Function Name | Input Arguments | Output |
|---|---|---|---|
| GeoJSON and JSON | SDO_UTIL.TO_GEOJSON | a geometry value (as an SDO_GEOMETRY object) | the geometry value in GEOJSON format (as a CLOB) |
| | SDO_UTIL.TO_GEOJSON_JSON | a geometry value (as an SDO_GEOMETRY object) | the geometry of type JSON in GeoJSON format |
| | SDO_UTIL.TO_JSON and SDO_UTIL.TO_JSON_VARCHAR | a geometry value (as an SDO_GEOMETRY object) | the JSON representation of that geometry (respectively as a CLOB or as a VARCHAR2) |
| | SDO_UTIL.TO_JSON_JSON | a geometry value (as an SDO_GEOMETRY object) | the JSON object for that geometry |
| | SDO_UTIL.FROM_GEOJSON | a geometry in GEOJSON format (as a VARCHAR2 or as a CLOB or as a JSON), crs parameter (as a VARCHAR2, now by default set to NULL, reserved for future use) and a SRID (as a VARCHAR2, by default set to 4326) | the geometry value for that GeoJSON representation (as an SDO_GEOMETRY object) |
| | SDO_UTIL.FROM_JSON | a geometry in JSON format (as a JSON object or as a CLOB), crs parameter (as a VARCHAR2, now by default set to NULL, reserved for future use) and a SRID (as a VARCHAR2, now by default set to -1, reserved for future use) | the geometry value for that JSON representation (as an SDO_GEOMETRY object) |
| KML | SDO_UTIL.TO_KMLGEOMETRY | a geometry value (as an SDO_GEOMETRY) | the geometry value in KML language (as a CLOB) |
| | SDO_UTIL.FROM_KMLGEOMETRY | a geometry in KML language (as a VARCHAR2 or a CLOB) | the geometry value for that KML representation (as an SDO_GEOMETRY object) |

Table 7. Functions related to GeoHash format from SDO_CS package in Oracle XE 21c (based on [49])

| Function Name | Input Arguments | Output |
|---|---|---|
| SDO_CS.TO_GEOHASH | an element of SDO_GEOMETRY type and geohash length (as a NUMBER) | the geohash value for that geometry (as a VARCHAR2) |
| SDO_CS.FROM_GEOHASH | a geohash value (as a VARCHAR2) and a SRID (as a NUMBER) | a geometry value of SDO_GEOMETRY type representing a specified geohash |

TABLE 8. Functions related to WKT and EWKT formats in PostGIS 3.4 (based on [55])

| Format | Function Name | Input Arguments | Output |
|---|---|---|---|
| WKT | ST_AsText | a geometry value of a geometry or geography type (or a geometry value and additional parameter used to reduce the maximum number of decimal digits after floating point used in output) | the WKT representation of the given geometry (as a text) |
| | ST_WKTToSQL (this is an alias name for ST_GeomFromText that takes no SRID) | a WKT representation of a geometry value (as a text) | the geometry value for that WKT representation (as element of a geometry type) |
| | ST_GeomFromText and ST_GeometryFromText | a WKT representation of a geometry value (as a text) (then SRID is default equal to 0) or a WKT representation of a geometry value and a SRID (as an integer) | the geometry value for that WKT representation (as element of a geometry type) |
| | ST_PointFromText, ST_LineFromText, ST_PolygonFromText, ST_GeomCollFromText, ST_MPointFromText, ST_MLineFromText, ST_MPolyFromText | a WKT representation of geometry value of an appropriate type (as a text) (then SRID is default equal to 0) or a WKT representation of a geometry value and a SRID (as an integer) | the geometry of an appropriate type for that WKT representation (i.e. POINT, LINESTRING, POLYGON, GEOMETRYCOLLECTION, MULTIPOINT, MULTILINESTRING, MULTIPOLYGON, respectively) as an element of geometry type, or null if the WKT is not describing the geometry from an appropriate class |
| | ST_BdPolyFromText | a WKT representation of a MultiLineString for an arbitrary collection of closed linestrings (as a text) and a SRID (as an integer) | the Polygon for that WKT representation (as an element of a geometry type) |
| | ST_BdMPolyFromText | a WKT representation of a MultiLineString for an arbitrary collection of closed linestrings (as a text) and a SRID (as an integer) | the MultiPolygon for that WKT representation (as an element of a geometry type) |
| EWKT | ST_AsEWKT | a geometry value of a geometry or geography type and some optional parameter with maximum number of decimal digits in output ordinates | the EWKT representation of the given geometry (that is a WKT representation with SRID metadata) (as a text) |
| | ST_GeomFromEWKT | a EWKT representation of a geometry value (as a text) | the geometry value for that EWKT representation (as element of a geometry type) |
| WKT or EWKT | ST_GeogFromText and ST_GeographyFromText | a EWKT or a WKT representation of a geometry value (as a text) | the element of a geography type (with SRID 4326 if it is unspecified) for that representation |

Table 9. Functions related to WKB, EWKB, HEXEWKB and TWKB formats in PostGIS 3.4 (based on [55])

| Format | Function Name | Input Arguments | Output |
|---|---|---|---|
| WKB | ST_AsBinary | a geometry value of a geometry or geography type (or a geometry object and some encoding parameter) | the WKB representation of the given geometry (as a bytea) |
| | ST_WKBToSQL (this is an alias name for ST_GeomFromWKB that takes no SRID) | a WKB representation of a geometry value (as a bytea) | the geometry value for that WKB representation (as element of a geometry type) |
| | ST_GeomFromWKB | a WKB representation of a geometry value (as bytea) (then SRID is default equal to 0) or a WKB representation of a geometry value and a SRID (as an integer) | the geometry value for that WKB representation (as element of a geometry type) |
| | ST_PointFromWKB, ST_LineFromWKB or ST_LinestringFromWKB | a WKB representation of a geometry value (as bytea) (then SRID is default equal to 0) or a WKB representation of geometry value and a SRID (as an integer) | the geometry of an appropriate type (POINT, LINESTRING) for that WKB representation as an element of a geometry type, or null if the WKB is not describing the geometry from an appropriate class |
| EWKB | ST_AsEWKB | a geometry value of a geometry type (or a geometry value and some encoding parameter) | the EWKB representation of the given geometry (that is a WKB representation with SRID metadata) (as a bytea) |
| | ST_GeomFromEWKB | a EWKB representation of a geometry value (as bytea) | the geometry value for that EWKB representation (as element of a geometry type) |
| WKB or EWKB | ST_GeogFromWKB | a EWKB or a WKB representation of a geometry value (as a bytea) | the geometry value for that representation (as element of a geography type) |
| HEXEWKB | ST_AsHEXEWKB | a geometry value of a geometry type (or a geometry value and some encoding parameter) | the HEXEWKB representation of the given geometry (that is in the hexadecimal numeral system) (as a text) |
| TWKB | ST_AsTWKB | a geometry value of a geometry type (or an array with a geometry collection) and some additional parameters | the TWKB representation of the given geometry (as a bytea) |
| | ST_GeomFromTWKB | a TWKB representation of a geometry value (as a bytea) | the geometry value for that TWKB representation (as element of a geometry type) |

TABLE 10. Functions related to GML, GeoJSON, KML and GeoHash formats in PostGIS 3.4 (based on [55])

| Format | Function Name | Input Arguments | Output |
|---|---|---|---|
| `GML` | `ST_AsGML` | a geometry value of a geometry or geography type and some additional parameters (one of the parameters concerns version of GML, may be either 2 or 3, 2 is a default value) | the GML representation of the given geometry value (as a text) |
| | `ST_GMLToSQL` and `ST_GeomFromGML` | a GML representation of a geometry value (as a text) or a GML representation of a geometry value and SRID as (an integer) | the geometry value for that GML representation (as a geometry) |
| `GeoJSON` | `ST_AsGeoJSON` | a geometry value of a geometry or geography type or record feature and the name of geometry column (and some optional parameters) | the GeoJSON representation for that geometry (a GeoJSON geometry object, or the row as a GeoJSON feature object, both written as a text) |
| | `ST_GeomFromGeoJSON` | a GeoJSON representation of a geometry value (as a text, json or jsonb) | the geometry value for that GeoJSON representation (as a geometry) |
| `KML` | `ST_AsKML` | a geometry value of a geometry or geography type and some optional parameters | KML representation of the given geometry value (as a text) |
| | `ST_GeomFromKML` | a KML representation of a geometry value (as a text) | the geometry value for that KML representation (as a geometry) |
| `GeoHash` | `ST_GeoHash` | a geometry value of a geometry type and some optional parameter | the GeoHash representation of the geometry (as a text) |
| | `ST_GeomFromGeoHash` | a GeoHash value (as a text) and some optional parameter | the geometry value for that GeoHash (as a geometry) |
| | `ST_Box2dFromGeoHash` | a GeoHash value (as a text) and some optional parameter | the geometry value for that GeoHash (as a box2d) |
| | `ST_PointFromGeoHash` | a GeoHash value (as a text) and some optional parameter (telling how many characters from the GeoHash is used to create the point) | the point that represents the center point of the geometry from a given GeoHash value |

TABLE 11. The availability of functions supporting a given format in MySQL 8.0, Oracle XE 21c and PostGIS 3.4/PostgreSQL 14

| Format | MySQL | Oracle XE | Postgis/PostgreSQL |
|---|---|---|---|
| WKT | ✓ | ✓ | ✓ |
| EWKT | | | ✓ |
| WKB | ✓ | ✓ | ✓ |
| EWKB | | | ✓ |
| TWKB | | | ✓ |
| HEXEWKB | | | ✓ |
| GML | | ✓ | ✓ |
| GeoJSON | ✓ | ✓ | ✓ |
| GeoHash | ✓ | ✓(with some problems) | ✓ |
| KML | | ✓ | ✓ |

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