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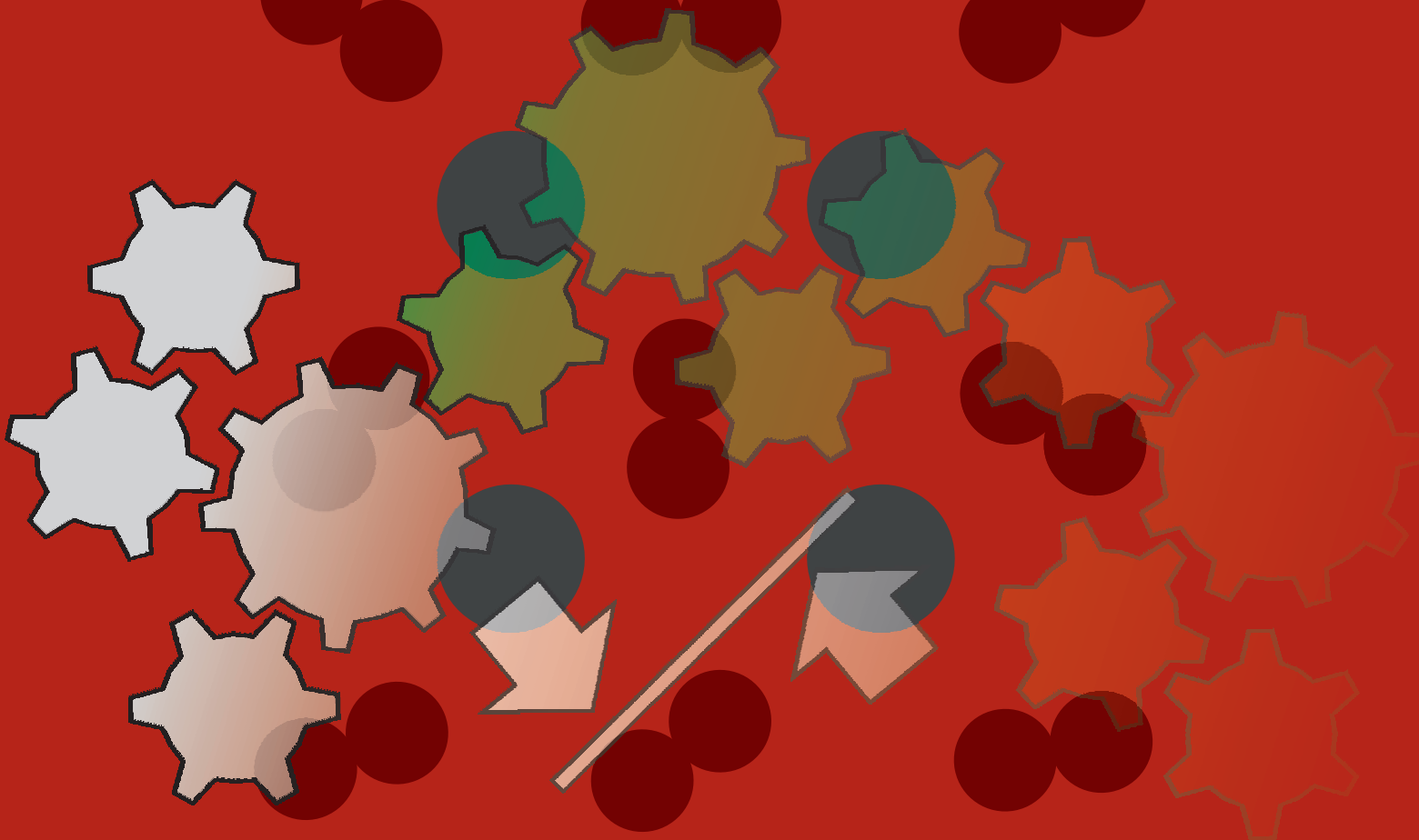
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Modelling the influence of transport accessibility, safety and affordability on mobility patterns among domestic workers in the City of Johannesburg

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Abstract: Household workers face transportation challenges, including limited access to safe, affordable, and reliable public transport, which constrains their mobility and promotes socio-economic exclusion. This study investigated the effects of transport accessibility, affordability, and perceptions of safety on live-out domestic workers' mobility in the City of Johannesburg, South Africa. With a 233-participant cross-sectional survey and Partial Least Squares Structural Equation Modelling (PLS-SEM), the study analyses both direct and mediated relationships between mobility patterns, affordability, perceptions of safety, and transport accessibility. The results reveal that perceptions of safety and transport accessibility have a direct effect on mobility patterns with less direct impact by affordability. Results demonstrate how safety perceptions operate as the intermediary between transport accessibility and mobility activities that signifies the importance of secure transit settings to adopt this low-income, female-dominated workforce. The study developed and tested a model of transport access and mobility to investigate how transport accessibility, safety perceptions, and cost influence commuting behaviours in this low-income, predominantly female workforce. Future research can use this model to examine similar factors in other locations. The study highlights the need for inclusive transport policy that integrates human flow management and material flow optimization within urban logistics systems.

1 Introduction

Domestic workers constitute an important and yet "invisible" segment of the informal labor force, making possible essential care for households and economic development more broadly [1]. As laborers hired to perform domestic tasks such as cleaning, cooking, childcare, elderly care, and other household services, domestic workers hold households together, enabling employers to seek activities outside the home [2]. In the United States alone, there are an estimated 2.2 million domestic workers, who are primarily women and immigrants and offer essential household services [3]. Spain, France, and Italy have some of the largest national workforces in Europe, with Spain alone accounting for an estimated 700,000 domestic workers, about 30% of whom are immigrants [4]. In the Middle East, particularly Oman and Kuwait, demand for domestic workers has risen steeply with economic development, urbanization, and a dependence on migrant labour. In Oman, there are over 158,537 migrant domestic workers, a significant number of whom are of South and Southeast Asian origin [5]. In Kuwait, domestic workers make up a sizeable number of the foreign workforce, with an estimated 660,000 employed in Kuwaiti households, comprising around 16% of the total population [6]. The 2021 Australian Census reported 258,000 people employed in residential aged care services in Australia [7]. According to Statistics South Africa, in the third quarter of 2024, approximately 854,000 domestic work jobs were recorded just below pre-pandemic peaks. These workers are predominantly female, constituting an estimated 80% of the global domestic worker base, again highlighting the highly gendered nature of this sector of work. Domestic work can either be paid or unpaid work, and paid domestic workers are typically hired and paid by households, while unpaid domestic work is most often performed by household members without receiving direct payment. Despite their making enormous contributions to both household functioning and the economy, domestic workers are typically underappreciated, some of this being due to social attitudes which frame domestic work as women's natural role [8]. With patterns like urbanization, expanding populaces, and maturing populations, the interest for domestic laborers continues to increase globally. Asia, and China in particular, has witnessed significant growth in the domestic work sector, powered by rising family income and an aging populace.

Domestic workers in South Africa are divided into two groups: "live-in" and "live-out" (Ally, 2010). This research focuses on "live-out" domestic workers, who travel daily to their employers' residences in urban locations. These workers face unique transport challenges, as their work opportunities and mobility are greatly influenced by the accessibility,

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affordability, and safety of available transport. Commuter transportation is necessary to support the livelihoods of such workers, moving from townships and informal settlements into urban centres such as the City of Johannesburg. However, the existing transport infrastructure does not generally cater to the needs of low-income commuters, and most domestic workers are forced to depend on minibus taxis and other informal transport systems, which are usually characterized by unstructured schedules and minimal safety features. These commuting challenges reflect disruptions in the flow of human capital, which is a critical element in urban logistics planning and labour mobility systems.

Despite increasing attention to urban mobility and gendered access to transport, there is limited empirical research exploring how transportation systems in African urban contexts influence the commuting experiences of low-income female workers. In particular, the literature lacks data-driven models that address the interrelated effects of accessibility, affordability, and safety on domestic workers' mobility patterns. Prior research has tended to treat these factors in isolation, without modelling their combined influence or capturing the lived realities of informally employed women in post-apartheid urban South Africa. This study addresses that gap by applying a structural equation modelling (SEM) approach to analyse the direct and mediated effects of these variables. The findings are expected to inform transport and labour policies that are more inclusive, equitable, and reflective of the needs of vulnerable populations in the global South.

Domestic workers are prone to "transport poverty," with high costs, low availability, and security concerns limiting their mobility, limiting access to secure work and essential services [9]. The female dominance in domestic work is subjected to higher risks, especially when travelling during early morning or late evening hours, putting them at higher risk of crime and harassment [10]. Dependence on informal transit systems continues to sustain a cycle of social and economic marginalization, thus the call for participatory transport policy that addresses the needs of such a workforce.

This study therefore aims to develop a model of transport access and mobility to address the transport issues and needs of live-out domestic workers in the City of Johannesburg, South Africa. The model also emphasizes the need for more responsive transport policies that are inclusive and better meet the needs of low-income, female-dominant workforces like domestic workers. Even though the finding of this research draws on the specific context of South Africa, the existence of domestic worker lives in other developing nations is not dissimilar, particularly regarding access to transport and transport-related safety issues. With this research, it aims to contribute voices that can support transport and policy-making interventions not just in South Africa but in other comparable city settings where informally working marginalized workers have challenges in accessing safe, accessible, and affordable transportation vehicles. These research objectives were answered by this research:

1. To examine the relationship between transport accessibility and safety perceptions among domestic workers in the City of Johannesburg, South Africa.
2. To analyze the effect of transport accessibility and affordability on mobility patterns of domestic workers in the City of Johannesburg, South Africa.
3. To analyze the effect of transport accessibility and safety perceptions on mobility patterns of domestic workers in the City of Johannesburg, South Africa.
4. To analyse how safety perceptions and affordability influence the interaction between transport accessibility and mobility patterns in the City of Johannesburg, South Africa.

This paper begins with a description of problems and objectives in an introduction, then literature review setting the key terms and related studies. Conceptual framework and hypothesis development offers theoretical bases, and research methods provide quantitative approach, sampling, and analysis techniques. Measurement and structural model tests test model reliability and validity and go on to hypotheses testing and results discussion. The conclusion summarizes contributions, implications for policy, and avenues for future research, with a theoretical framework provided in the next section.

2 Literature review

2.1 Theory grounding the study

Transportation equity theory offers a useful framework for understanding transportation issues in South Africa, a nation where apartheid-related spatial inequalities persist in affecting transport access and economic opportunities. This theory argues that fair access to transport is essential for socio-economic inclusion, stating that everyone, irrespective of income, gender, or type of employment, should be able to access affordable, safe, and reliable transport to engage fully in economic, social, and civic life [11]. When transport systems fail to provide such access, marginalized groups such as low-income, female, and informal sector workers are at risk of "transport poverty," the condition where limited transport options constrain access to desired services and entrench social and economic inequalities. Transportation equity theory identifies three critical components: affordability, accessibility, and safety. Affordability is making transport fares

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accessible to low-income communities, making it possible to remove cost barriers to employment, health, and education services [12]. Accessibility is offering transport services at accessible locations, frequencies adequate to connect people to important destinations [13]. Safety is especially important for vulnerable groups, such as female domestic workers who are more likely to be subjected to harassment or violence, particularly when they travel late at night using minimal security measures [14]. South African poor workers, including domestic workers, also prefer to live in townships and informal settlements outside major cities, far from those places of work. Such physical isolation and limited public transport system carries a substantial time and cost burden, ensuring continued poverty and social isolation. Higher than affordable transport costs up to 20% of a monthly wage for some highlight the need for affordable transport [15]. Limited-service coverage and schedules ensure most destinations are under-serve, resulting in increased "transport poverty" and constricting opportunities to employment and services. Safety is also a concern, with high crime rates, lighting, and surveillance shortages in transport environments further discouraging public transport use and limiting mobility options, particularly for female workers. Transportation equity theory is applied within this study to advocate for transport policies that are inclusive to all in South Africa by lowering affordability, accessibility, and safety obstacles. Enhancing subsidies, increasing the coverage of services, and improving provision of safety would assist significantly in enabling equal access to transport among domestic workers and other vulnerable individuals, enhancing narrowed socio-economic disparities and increased social inclusion. The following section addresses the effect of transport accessibility on perceptions of safety.

2.2 *Transport accessibility and safety perceptions*

Transport safety and perceptions of accessibility are closely related and jointly determine the overall perception of public transport accessibility, with consequences for commuter experience and travel behavior. From a logistics management perspective, transport accessibility can be understood as a function of how efficiently information and human flows are coordinated across transport nodes [16]. This is influenced by factors like service frequency, reliability, and proximity to stops. Accessible public transport is vital for social inclusion, enabling individuals to engage fully in work, leisure, and social activities [17]. Excellent service quality, especially functionality (e.g., dependable schedules, high frequency of service, and accessible stop points), significantly contributes to perceived accessibility, rendering public transport a viable and desirable alternative for a greater number of people [18]. Nevertheless, frequent users of public transport experience lower perceived accessibility after prolonged exposure to constraints or dissatisfaction with the services, showing that perceptions of quality and safety are needed to align in the direction of a preferred commuter experience. Safety perceptions encompassing physical security and personal safety are necessary to make accessibility possible. These emotions include a variety of concerns, such as fear of crashes, crime, or disease threats. Those who feel unsafe are more likely to avoid public transport or limit their travel habits, especially in certain locations or times. Olsson, Friman and Lättman [19] explained that perceived safety is directly related to perceived accessibility. A safe environment enhances the comfort and likelihood of frequent use of public transport by the traveler. Key factors that develop a positive safety mentality are well-established infrastructure, seen security measures, and open communication during delays, which collectively act to increase transport system confidence. The link between transport access and safety impression is thus cross-dependent and symbiotic. While accessibility attributes, such as good service and closeness encourage frequent usage, a sense of safety reinforces this accessibility, facilitating increased commuter trust and promoting accessible, sustainable public transport systems. Therefore, both accessibility and safety play a very positive role in enhancing the perceived accessibility of public transport and thus making it more appealing as a substitute for private cars, especially in cities.

2.3 *Transport accessibility and affordability*

Transport accessibility affects affordability by influencing the efficiency of material and human flows across the urban transport logistics network. Live-out domestic workers in cities like Centurion in South Africa face high transport costs, long commutes, limited access to affordable modes (e.g., no rail), and safety concerns during non-standard hours [20]. Serebrisky, Gómez-Lobo, Estupiñán and Muñoz-Raskin [21] find that most current policies, especially supply-side subsidies given to operators, are either neutral or regressive and do not significantly benefit the poorest. The study recommends shifting toward demand-side subsidies targeted at users and integrating transport subsidies with broader poverty alleviation strategies such as cash transfers or access to essential services. They continue that fare subsidies, as well as the expansion of Metro and bus networks, render transport more accessible to these groups, allowing greater mobility and accessibility to social services. Guzman, Oviedo and Rivera [22] concentrate on Bogotá's pro-poor subsidy program and emphasize that subsidies eliminate the "time poverty" that economically disadvantaged groups face when transport provision is either absent or costly. Their finding aligns with Brown [23], who note that fare subsidies negate socioeconomic imbalances by allowing low-income commuters to avoid costly trips by other transport modes.

The study concludes that not only do these policies enhance affordability, but also that they offer support for job accessibility, creating equitable transport environments. Dewita, Burke and Yen [24] highlight in their study of Indonesia that both accessibility and affordability matter to sustainable urban growth because transport spending often represents a

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significant share of household spending. They promote that targeted subsidies, fare reduction, and enhanced accessibility can ensure low-income populations still could travel without incurring financial burdens. Similarly, Obudho, Otengah and Shivachi [25] examine how motorcycle taxis in rural Kenya serve as a low-cost, accessible transport mode, addressing the mobility needs of underserved populations. Although based in a rural context, their findings reinforce the idea that informal transport solutions can play a vital role in improving transport equity and affordability for vulnerable communities. Kębłowski [26] demonstrated that subsidization of public transport specifically for vulnerable or low-income populations improves overall urban equity by reducing the cost burden of transit. Thus, augmenting spatial accessibility in conjunction with fare affordability measures can achieve greater transport equity by reducing both the direct and indirect costs of commuting for disadvantaged groups, as studies in different world city contexts have shown.

2.4 Affordability and mobility patterns

Continuing with the importance of affordability and its impact on mobility behavior, research demonstrates how unaffordable transport diminishes low-income household access to essential services to a significant degree. For instance, Venter [27] demonstrates how issues of affordability compel most South Africans to spend excessively high proportions of their travel costs, with the poor spending as much as 21% of the household expenditure on travel. This expense is likely to lead to restrained mobility, where individuals limit their travel to necessary trips only, and this has a negative impact on their job and access to social services. Perrotta [28] explains that the fare expense is an essential factor determining public transport affordability among low-income passengers since excessive fares reduce access to employment, healthcare, and education. This impact, magnified in urban contexts with spatial imbalances like Cape Town, has prompted targeted subsidies to raise transport affordability. Effective subsidy initiatives are critical to improving the affordability of transport among the poor, promoting greater mobility and access to economic opportunities. Vitale Brovarone [29] support a shift from mobility-oriented planning to accessibility-based policies. He believes that upgrading low-cost transportation modes, such as transit-oriented development (TOD) and low-cost housing near job centers, can reduce the overall cost of transportation for poor households. This kind of planning based on accessibility not only makes transport more affordable but also promotes economic and social inclusion by minimizing far-reaching commutes. Porter [30] determined that transport affordability directly impacts livelihood outcomes in low-income urban environments in developing nations. They add that fare increases have the potential to discourage poor people from traveling, thereby containing them further within poverty circles. According to their study, fare control and strategic subsidy can prove to be an effective catalyst to promote accessible and affordable modes of transportation in economically mixed cities. These findings emphasize the role of logistics elements such as flow coordination and transport cost efficiency in determining sustainable commuting behaviour.

2.5 Safety perceptions on mobility patterns

Safety perceptions have a strong effect on mobility behavior, typically overriding concrete safety measures in the formation of travel patterns. Studies observe that safety perceived, mediated by ambient conditions, feelings, and neighborhood structure, decides on the willingness of individuals to adopt varied mobility modes. For example, whereas walkability of a neighborhood is bound to encourage active travel, it will also heighten collision risk, creating a trade-off in which people limit mobility if a place is not considered safe. Design elements like mixed land use and controlled traffic speed are found to boost safety perception, while Lee, Zegras and Ben-Joseph [31] say excessive traffic flow and weak surveillance will deter walking and public transport use. Ceccato, Gaudalet and Graf [32] add that facilities such as lighting, cleanliness, and surveillance, following Crime Prevention Through Environmental Design (CPTED) principles, enhance perceptions of safety, particularly in the context of public transportation areas. Meanwhile, Oxley and Whelan [33] find that also affecting mobility limitations is the area perception of safety, where unsafety in the environment restricts spontaneous mobility and participation in physical activity, especially in vulnerable populations. Enhancing perceived safety through thoughtful urban design and maintenance can promote more flexible, frequent mobility choices in many communities.

2.6 Transport accessibility on mobility patterns

Transport accessibility also has a significant impact on influencing individuals' mobility patterns by informing choices on mode of travel, frequency, and destination. Literature is more likely to emphasize the link between accessible transport and enhanced mobility, particularly in urban areas with varying degrees of accessibility based on distance to public transport, connectivity, and service frequency [34]. Behavioral studies argue that if transport choice exists, individuals will engage in activities requiring travel, developing customary mobility habits and a broad range of travel routines. Travel frequency and implications of travel destinations demonstrate how access opens or limits individual and economic mobility, especially in urban or socio-economically diverse locations. Urban planning has a great impact on transport accessibility. Areas of high density with well-integrated transport have more stable mobility because the residents have easy access to various modes of transit. Such urban accessibility fosters normal commuting behavior, impacting social and career opportunities. Obstacles in accessibility are likely to be linked with reduced social mobility since the resident's

face obstacles in job accessibility, educational exposure, and social interaction. Limited access can further widen socio-economic cleavages by constraining mobility for the poor, thereby influencing urban policy and planning. Optimising passenger flow and information systems in urban settings improves accessibility and commuting efficiency.

2.7 Mediation effect of safety perceptions on the relationship between transport accessibility and mobility patterns

Transport accessibility, perceptions of safety, and mobility patterns are integrated in a dynamic system in which each variable influences people's commuting decisions. Transport accessibility has a direct influence on mobility in that it dictates the range of travel options, with higher accessibility generally stimulating varied mobility patterns by being convenient and flexible [35]. Safety perceptions, however, act as an important filter, modifying the way in which accessibility is converted into actual travel behaviour. Available transport options, when perceived to be insecure due to issues like poor infrastructure or crime problems, are likely to be avoided, particularly by vulnerable groups like the elderly and females [14]. This leads to selective mobility patterns, with people adapting by choosing modes of transportation or routes that are aligned with their comfort zones for safety, such as not traveling late or taking private forms of transportation even where public transportation is available [36]. As such, feelings of safety tend to mediate the relationship between accessibility and mobility, particularly in urban regions where safe but inaccessible transit lines are underutilized. This is supported by empirical studies, where travellers tend to prioritise security over accessibility in unsafe environments, influencing underutilization patterns and selective route choice [37]. These results suggest that transport policies aimed at improving accessibility also address safety through secure infrastructure and public safety measures, encouraging more equitable and widespread utilization of accessible transport facilities [38].

2.8 Mediation effect of affordability on the relationship between transport accessibility and mobility patterns

The mediating impact of affordability within the relationship between transport accessibility and mobility behaviour highlights that money limits travel decision-making even when there is accessible transport. Good transport accessibility would otherwise enable flexible and diverse mobility behaviour by making convenient means of transport accessible, yet without affordability, these accessible means of transport remain out of reach [39]. Affordability acts as an economic filter, determining which transport modes are viable among those that exist, especially for low-income earners who will walk, carpool, or take informal transit modes when they are too costly [40]. Research on low-income and rural communities indicates that even where public transport exists, affordability limitations result in underuse of available modes, further demonstrating affordability's influence on mobility behaviour [41]. Consequently, effective transport policies must include affordability through subsidized fares, reduced-cost travel cards, and affordable and accessible transport like shared bikes or ride-sharing programs, ensuring that accessibility translates into stable and efficient mobility behaviours. This conflict between affordability and accessibility highlights the need for inclusive transportation policy permitting accessible alternatives to foster diverse and equitable mobility trends among socio-economic communities.

3 Conceptual framework

The current study is based on transport access and mobility model that tests the influence of transport accessibility on mobility patterns through safety perceptions and affordability by domestic workers in the City of Johannesburg, South Africa, as outlined in Figure 1. The model establishes four constructs of central importance: Transport Accessibility (TA), Safety Perceptions (SP), Affordability (AF), and Mobility Patterns (MP). The model has direct and indirect associations, consisting of seven hypotheses overall. Specifically, it supposes that the connection between Transport Accessibility (TA) and Mobility Patterns (MP) is intermediated by Safety Perceptions (SP) and Affordability (AF). Five direct connections between these variables are obviously revealed through the conceptual model. Hypotheses Transport Accessibility (TA), Safety Perceptions (SP), Affordability (AF), and Mobility Patterns (MP) are indicated in Figure 1.

This study sought to test empirically seven hypotheses using the proposed model, namely:

Hypothesis 1: Transport accessibility influences safety perceptions among domestic workers in the City of Johannesburg, South Africa.

Hypothesis 2: Transport accessibility influences affordability among domestic workers in the City of Johannesburg, South Africa.

Hypothesis 3: Affordability influences mobility patterns among domestic workers in the City of Johannesburg, South Africa.

Hypothesis 4: Safety perceptions influence mobility patterns among domestic workers in the City of Johannesburg, South Africa.

Hypothesis 5: Transport accessibility influences mobility patterns among domestic workers in the City of Johannesburg, South Africa.

Hypothesis 6: The effect of transport accessibility on mobility patterns is mediated by safety perceptions among domestic workers in the City of Johannesburg, South Africa.

Hypothesis 7: The effect of transport accessibility on mobility patterns is mediated by affordability, among domestic workers in the City of Johannesburg, South Africa.

The next section provides the methodology used in this study to collect data from the respondents.

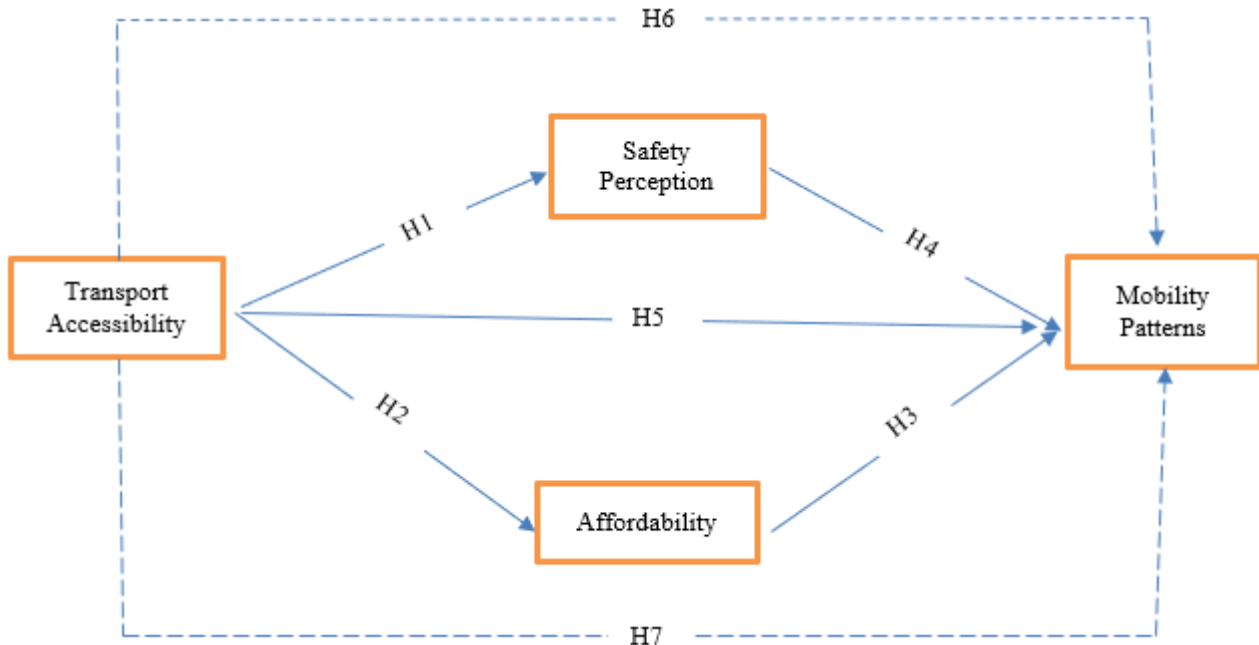


Figure 1 Transport access and mobility model for domestic workers in South Africa

Source: author (2024)

4 Research methods

The present study employed cross-sectional survey design under the quantitative study design framework guided by a positivist worldview to explore how access to transport, safety perceptions, and affordability influence the mobility patterns of domestic workers in Centurion, City of Johannesburg. Using structural equation modelling (SEM) to estimate direct as well as indirect relationships, 233 domestic workers were randomly chosen using purposive sampling. A standardized questionnaire, from validated scales, was employed to measure demographics, transport accessibility, safety perceptions, affordability, and mobility behaviours, with each area specifically crafted to determine domestic workers' special commuting challenges (Refers to Table 1). A pilot interview of 10 domestic workers enabled the calibration of the questionnaire to be simple and consistent. Data were gathered over four weeks in paper and digital forms, reaching the respondents through association meetings and community centres. Partial least squares structural equation modelling (PLS-SEM) was applied to analyze data to evaluate the measurement model using Cronbach's alpha, composite reliability, average variance extracted (AVE), and HTMT ratio for reliability and validity and the structural model in which bootstrapping tested path coefficients and mediation effects. Standardised root mean square residual (SRMR) was used to test model fit. The methodological approach is a comprehensive and precise examination of commuting experience variables among domestic workers that provide insight into their mobility and socio-economic constraints they are exposed to Table 1 presents the measurement scales and sources.

Age distribution of the 233 respondents in this research reveals that most of the domestic workers were aged 46-55 years (33.9%), and secondly, they were between the ages of 36-45 years (20.6%). Most of the respondents were unmarried (67.8%), and 32.2% were married. This one majority reflects socio-economic determinants that may affect the composition of the home-based workforce, where singleness is likely to be aligned with the needs or availability of this occupation. The earnings information reveals that 49.8% of the respondents earn between R4100 and R4500, and 30.0% earn more than R4600. The 20.2% earn between R3600-4000. No respondent's income was in the lowest category (R250-R3500), reflecting a clustering of incomes at moderate but not lowest levels. This income distribution is typical of the comparative low-wage foundation of the industry. Most respondents, 62.2%, make use of R400-R600 in monthly transport costs. The next substantial group, 21.9%, spend R700-R900, and 15.9% spend a further R1000 a month. These transport expenses reflect a significant percentage of their own monthly earnings spent on commutes, highlighting the economic burden these workers are under with their low income. The following section provided the findings of the SEM conducted for this research.

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Table 1 Measurement scales and their sources

Construct	Measuring Items	Sources
Transport Accessibility (TA)	1. TA1: The distance from my residence to the nearest public transport stop is convenient. 2. TA2: The frequency of public transport services is adequate for my needs. 3. TA3: Public transport services are reliable and operate on time. 4. TA4: The location of transport stops/stations is convenient. 5. TA5: I have access to different modes of transport for commuting.	Friman, Lättman and Olsson [42], Olsson, Friman and Lättman [43]
Safety Perceptions (SP)	1. SP1: I feel safe waiting at public transport stops. 2. SP2: Public transport vehicles are safe from accidents or crime. 3. SP3: There are visible security measures at stops. 4. SP4: Lighting is adequate at public transport stops and on my route. 5. SP5: Public transport services prioritize passenger safety.	Abenoza, Cats and Susilo [44], Ceccato and Paz [14]
Affordability (AF)	1. AF1: The cost of public transport is affordable based on my income. 2. AF2: I can use public transport regularly without financial strain. 3. AF3: Public transport offers good value for money. 4. AF4: I can access different transport options that fit within my budget. 5. AF5: Financial subsidies or discounts are available for users.	Dewita, Burke and Yen [45], Guzman, Oviedo and Rivera [22]
Mobility Patterns (MP)	1. MP1: I use public transport frequently for commuting. 2. MP2: I adjust my commuting patterns based on safety concerns. 3. MP3: I select my commuting routes based on affordability and accessibility. 4. MP4: The time I spend commuting is reasonable. 5. MP5: I avoid certain times or routes to ensure a safer commute.	Zegras, Lee and Ben-Joseph [46]

Source: author (2024)

4.1 Measurement model assessment

Partial Least Squares Structural Equation Modelling (PLS-SEM) was utilized to examine the relationships between latent constructs (e.g., affordability, mobility patterns, safety perception, and transport accessibility) and their respective manifest variables. PLS-SEM was chosen because of its ability to handle complex models with multiple constructs and indicators, and for being suitable when the research aim is more focused on prediction and theory development rather than simple theory confirmation [47]. The constructs were modelled reflectively, a decision founded on theoretical assumptions that latent variables manifest themselves in observable indicators. Reflective measurement models assume that change in the latent construct leads to change in the corresponding indicators [48]. This aligns with the nature of constructs in this study that were envisioned as underlying constructs with observable indicators to portray them. Table 2 provides a summary of measurement model evaluation results.

The internal consistency of every construct was established in Table 2 through composite reliability (CR) and Cronbach's alpha. The results, from Table 2, were that CR and Cronbach's alpha values were both over the acceptable cut-off of 0.7 at 0.887 to 0.898 for CR and 0.878 to 0.895 for Cronbach's alpha, confirming reliable measurement of all constructs. The convergent validity was checked by means of the Average Variance Extracted (AVE), which represents variance extracted by a construct in comparison to error measurement (Farrell, 2010). Table 2 shows that all the constructs possessed a sufficient convergent validity with AVE values more than 0.5, i.e., each construct extracts over 50% variance in its measures [49]. Reliability of the indicators was validated by verifying the loadings of every indicator on its respective latent construct, and it is generally expected that suitable loadings are greater than 0.7 [50]. All the indicators in Table 2 were greater than this level, therefore validating that each indicator is measuring its respective construct accurately. High indicator reliability ensures the contribution of each indicator towards a proper indication of its respective construct. The next section provides the findings of discriminant validity of the research.

Table 2 Measurement model assessment

Latent construct	Indicators	Indicator reliability	CR	AVE	Cronbach's alpha
Affordability	A1	0.782	0.890	0.672	0.878
	A2	0.853			
	A3	0.858			
	A4	0.793			
	A5	0.809			
Mobility Patterns	MP1	0.803	0.898	0.697	0.891

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	MP2	0.798			
	MP3	0.884			
	MP4	0.886			
	MP5	0.798			
Safety Perception	SP1	0.755	0.887	0.686	0.885
	SP2	0.854			
	SP3	0.855			
	SP4	0.823			
	SP5	0.851			
Transport Accessibility	TA1	0.742	0.896	0.710	0.895
	TA2	0.742			
	TA3	0.905			
	TA4	0.904			
	TA5	0.900			

Source: Author (2024)

4.2 Discriminant validity

The discriminant validity in the model was checked both using Fornell-Larcker criterion and the Heterotrait-Monotrait (HTMT) ratio such that each construct should be different conceptually from others. The Fornell-Larcker criterion is to contrast the square root of the Average Variance Extracted (AVE) for every construct with its correlation with other constructs, with higher diagonal values than any inter-construct correlations indicating discriminant validity. Results in Table 3 indicate that affordability ($\sqrt{AVE} = 0.820$), mobility patterns ($\sqrt{AVE} = 0.835$), safety perception ($\sqrt{AVE} = 0.828$), and transport accessibility ($\sqrt{AVE} = 0.842$) all surpass their correlations with other constructs, establishing that each construct has more variance in common with its indicators than with any other construct. The results of Fornell-Larcker criteria are shown in Table 3.

Table 3 Fornell-Larcker criterion

Constructs	Affordability	Mobility Patterns	Safety Perception	Transport Accessibility
Affordability	0.820			
Mobility Patterns	0.217	0.835		
Safety Perception	0.415	0.618	0.828	
Transport Accessibility	0.263	0.541	0.600	0.842

Source: author (2024)

Table 3 using the HTMT ratio, a conservative discriminant validity measure, also supports the finding because all values of construct pairs are below the 0.85 threshold (e.g., affordability and mobility patterns: 0.239; mobility patterns and safety perception: 0.689), fulfilling discriminant validity standards. Table 4 presents discriminant validity using the HTMT criterion.

Table 4 results based on both Fornell-Larcker criterion and Heterotrait-Monotrait (HTMT) ratio ensure that all constructs are unique and measure different concepts in the presented model, hence validating the outer measurement model for subsequent structural analysis. This study employed both the Fornell-Larcker criterion and the Heterotrait-Monotrait (HTMT) ratio to ensure a robust assessment of discriminant validity. The use of these two methods provides complementary insights in this study: the Fornell-Larcker criterion is a traditional but widely accepted approach that compares the square root of AVE to inter-construct correlations, while the HTMT ratio, as a more recent and conservative technique, assesses whether constructs are truly distinct by evaluating the average correlations across items of different constructs. Applying both tests enhances the reliability of discriminant validity assessment, aligning with best practices in Partial Least Squares Structural Equation Modelling (PLS-SEM). This dual approach ensures that the latent constructs used in the model are conceptually and statistically distinct, which is a prerequisite for valid structural path analysis. The results of structural model assessment are presented in the next section.

Table 4 Heterotrait-monotrait ratio (HTMT)

Constructs	Affordability	Mobility Patterns	Safety Perception
Affordability			
Mobility Patterns	0.239		
Safety Perception	0.470	0.689	
Transport Accessibility	0.293	0.601	0.675

Source: author (2024)

4.3 Structural model assessment

Structural model fit tests examine the association between latent constructs in terms of effect size and prediction accuracy, namely, adjusted R-square, effect size (f-square), and Variance Inflation Factor (VIF). These tests tell us about the strength of prediction of the model and the strength of associations between constructs [51]. R-square is the proportion of explained variance by the model for every endogenous construct that present evidence on the predictive ability of the model [52]. R-square results are presented in Table 5.

Table 5 R-square

Constructs	R-square
Affordability	0.069
Mobility Patterns	0.429
Safety Perception	0.359

Source: author (2024)

As is evident from Table 5, the R-square (R^2) assesses the predictive validity of the model for predicting each endogenous construct as a percentage of variance explained. Affordability's R^2 value is 0.069, which means that 6.9% of its variance is explained by the model, which suggests low predictive validity. Mobility patterns, however, are represented by an R^2 value of 0.429, which means that 42.9% of its variance is explained by the predictors, suggesting moderate predictive validity. Safety perception has an R^2 of 0.359, explaining 35.9% of the variance, and thus having moderate predictive accuracy too. These R^2 results suggest that while the model explains a moderate proportion of variance in mobility patterns and safety perception, its predictability for affordability is very low.

The f-square value provides an estimate of the effect size of a predictor on an endogenous construct, where 0.02, 0.15, and 0.35 represent small, medium, and large effects, respectively (Cohen, 1988). f-square (f^2) values estimate the effect size of each predictor on an endogenous construct in Table 6. The route affordability → mobility patterns have an f^2 value of 0.004, indicating a zero effect, i.e., there is no substantial effect of affordability on mobility patterns. Safety perception → mobility patterns have an f^2 value of 0.230, representing a medium effect size, and it suggests that safety perception is significantly related to mobility patterns. In Table 6, transport Accessibility → Affordability has an f^2 of 0.074, which is a small effect size, and transport accessibility thus has a moderate impact on affordability. Transport accessibility → mobility patterns have a small effect size with an f^2 of 0.080, and hence a modest effect of transport accessibility on mobility patterns. Yet, transport accessibility → safety perception has a large effect size with an f^2 of 0.561, indicating that transport accessibility has a considerable influence on safety perception. These f-square values represent various effect strengths, and the largest one is found between transport accessibility and safety perception. Table 6 lists the f-square values for every predictor variable, which represent effect size and VIF values in this model.

Table 6 F-square and VIF values

	VIF F	f-square
Affordability -> Mobility Patterns	1.208	0.004
Safety Perception -> Mobility Patterns	1.756	0.230
Transport Accessibility -> Affordability	1.000	0.074
Transport Accessibility -> Mobility Patterns	1.562	0.080
Transport Accessibility -> Safety Perception	1.000	0.561

Source: author (2024)

The VIF values check for multicollinearity between the predictor variables, with VIF values below 5 establishing low multicollinearity and, therefore, reliable estimates. All the VIF values in Table 6 are below 2, which represents very low multicollinearity between predictors and ensuring that multicollinearity was not an issue for this model. Results of model-fit statistics for this study are given in the subsequent section.

4.4 Model-fit statistics

Model-fit statistics assess the degree of the data-fitting suggested model, providing a measure of the general model adequacy. Among the common employed model-fit indices were the Standardized Root Mean Square Residual (SRMR), d_ULS (unweighted least squares discrepancy), d_G (geodesic discrepancy), Chi-square, and the Normed Fit Index (NFI). The results of the model-fit statistics are presented in Table 7.

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Table 7 Model fit indices

Model fit indices	Estimated model
SRMR	0.122
d_ ULS	3.140
d_ G	9.733
Chi-square	6262.704
NFI	0.344

Source: author (2024)

In Table 7, the SRMR of the estimated model is 0.122, which is greater than the widely accepted threshold of 0.08 for a good fit. This suggests a large difference between predicted and observed correlations, indicating that there could be scope for model fit improvement. d_ ULS is 3.140, one of the fit measures that compares discrepancies in the least squares sense. Though lower is better in terms of fit in general, the value suggests moderate discrepancies and where the model can be worked on. At a value of 9.733, d_ G (Geodesic Discrepancy) quantifies discrepancies in geodesic distance terms. Although there is no formal cutoff for d_ G, lower is preferred. The value here suggests that the model is not grossly misaligned but leaves some room for improvement. The Chi-square for the estimated model is 6262.704, testing the difference between observed and model-implied covariance matrices. High Chi-square values typically indicate poor fit, as the estimated model does not exactly capture the relationships observed in the data. The NFI (Normed Fit Index) of the estimated model is 0.344, with higher values near 1 indicating better model fit compared to a baseline model. An estimate of 0.344 suggests that the model is not well-fitted compared to the baseline and that structural change is required.

Figure 2 shows a structural equation model of relationships between latent constructs: transport accessibility, safety perception, affordability, and mobility patterns. The blue circles are each of the latent constructs, with figures inside them indicating the R-square (R²) value, which is the proportion of variance explained by the predictors for the construct. According to the model, transport accessibility has a high impact on safety perception and a moderate impact on affordability and mobility patterns. Safety perception, on the other hand, exerts a very strong positive influence on mobility patterns, the focal outcome variable in the model. affordability does not have a significant influence on mobility patterns. High indicator loadings between constructs are an assurance of the measures' reliability, and the model explains a moderate variance for mobility patterns and safety perception, but very little variance for affordability. Figure 2 is the result of the direct path analysis.

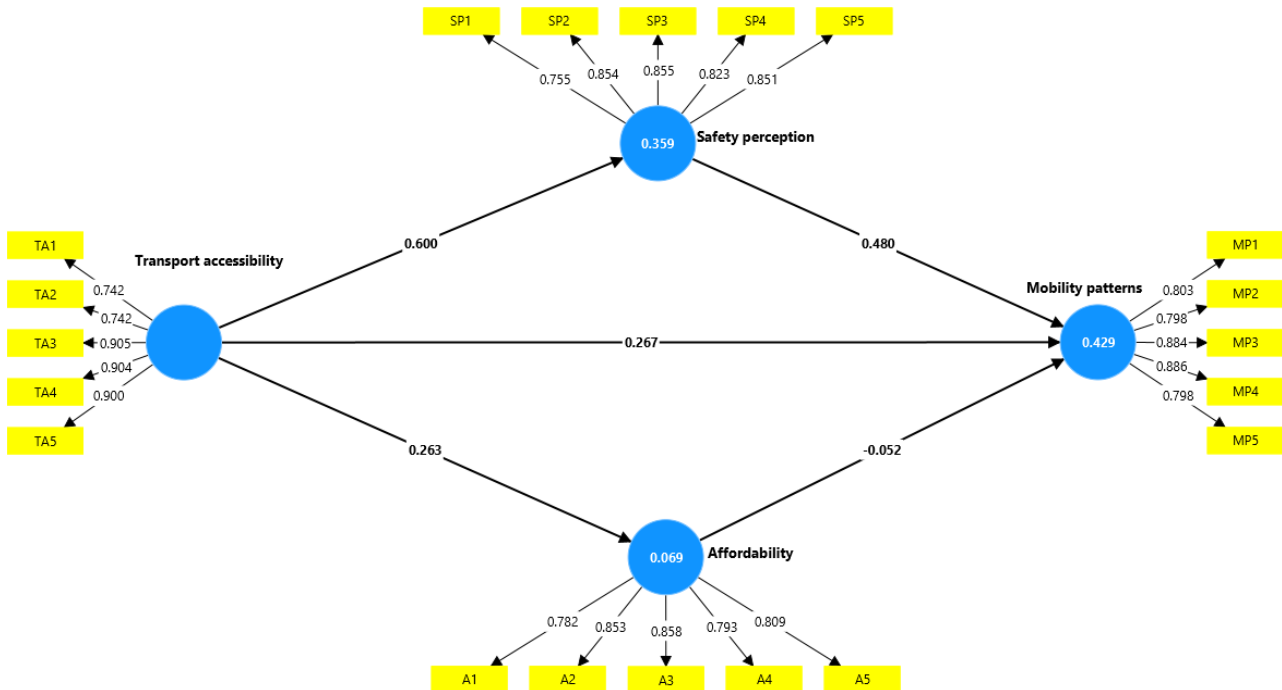


Figure 2 Transport access and mobility model for domestic workers in South Africa

Source: author (2024)

TA, transport accessibility, SP, safety perception, A, affordability, and MP, mobility patterns

* Significant at p <0.001

* Significant at t >1.96

The next section focuses on hypothesis testing.

4.5 Hypothesis testing

The study employed SEM in testing hypothesized structural relationships. Adopting Wong (2013), a threshold of more than 0.20 for standardized path coefficient was applied as significance, albeit in the model. Path coefficient significance was tested through bootstrapping with 5,000 iterations, with t-values higher than 1.96 at the 95% confidence level indicating significance. This method borrows from Hair et al. (2014), who propose using t-statistics and p-values obtained through bootstrapping to determine path significance with accuracy. The 0.20 threshold for standardized path coefficients is a standard measure in most research fields. Table 8 presents the path coefficient results estimated at a 95% confidence level.

Table 8 Results of direct path analysis

Paths	H	Path coefficient (β value)	T Values	p Values	Decision
Transport Accessibility -> Safety Perception	H1	0.600	12.639	0.000	Supported
Transport Accessibility -> Affordability	H2	0.263	4.428	0.000	Supported
Affordability -> Mobility Patterns	H3	-0.052	0.932	0.352	Not Supported
Safety perception -> Mobility Patterns	H4	0.480	6.063	0.000	Supported
Transport Accessibility -> Mobility Patterns	H5	0.267	3.745	0.000	Supported

TA, Transport Accessibility, SP, Safety Perception, A, Affordability, and MP, Mobility Patterns
 * Significant at p < 0.001.
 *Significant at T > 1.96.

Source: author (2024)

Table 8 hypothesis testing results indicate that transport accessibility has a significant effect on safety perception ($\beta = 0.600$, $t = 12.639$, $p = 0.000$), affordability ($\beta = 0.263$, $t = 4.428$, $p = 0.000$), and mobility behaviour ($\beta = 0.267$, $t = 3.745$, $p = 0.000$), confirming these associations. Outcomes reveal that perception of safety positively impacts mobility patterns ($\beta = 0.480$, $t = 6.063$, $p = 0.000$) with high influence on the outcome variable. The impact of affordability on mobility patterns ($\beta = -0.052$, $t = 0.932$, $p = 0.352$) is not statistically significant, indicating that affordability has no significant impact on mobility patterns. Overall, findings in Table 8 indicated the effects of transport accessibility and perceived safety as the significant predictors of mobility patterns, while affordability is less so. The subsequent section indicates the indirect path analysis of this study.

4.6 Mediation effect analysis

Mediation effect analysis is used to determine whether the impact of an independent variable (predicator) on a dependent variable (outcome) is mediated by a third variable, known as a mediator [53]. It is this concept, which was originally formulated by Baron and Kenny [54], establishing a causal theory of mediation to explain how an intermediary explains the mechanism or process through which one variable affects another. Mediation analysis answers the "how" and "why" behind relationships in several complicated models to increase theoretical knowledge as well as improve practical applications. More recently, for example, scholars such as Preacher and Hayes [55] have added to and further refined the process with a greater focus on bootstrapping methods in indirect effect estimation, offering increased robustness and better mediation assessment, especially where small samples are being dealt with, or distributions are non-normal. Mediation is considered significant when the indirect effect (the product of the relations between the predictor and the mediator, and the mediator and the outcome) is statistically distinct from zero, indicating that the mediator is significantly influencing the relationship [55]. Mediation analysis is commonly used when it is theorized by a researcher that the effect of one variable on another is mediated by an intervening construct [53]. For example, in this study, mediation effect analysis helps in understanding whether constructs such as safety perception and affordability transfer the effect of transport accessibility to mobility patterns. This approach not only strengthens theoretical models by illuminating back-end processes but also follows suggestions of researchers such as Hayes [56] and MacKinnon [53], who suggest reporting both direct and indirect effects to reveal the integrated architecture of relationships in a model. Indirect path analysis findings are presented in Table 9.

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Table 9 Results of indirect path analysis

Paths	Hypothesis	Path coefficient (β value)	T Values	p Values	Decision
Transport accessibility -> Safety perception -> Mobility patterns	H6	0.287	5.643	0.000	Supported
Transport accessibility -> Affordability -> Mobility patterns	H7	-0.014	0.872	0.383	Not Supported

TA, Transport Accessibility, SP, Safety Perception, A, Affordability, and MP, Mobility Patterns
 * Significant at $p < 0.001$.
 *Significant at $T > 1.96$.

Source: author (2024)

In Table 9, the mediation effect analysis reveals that safety perception effectively mediates the relationship between transport accessibility and mobility patterns with a path coefficient of 0.287, t-value of 5.643, and p-value of 0.000, which is a strong and statistically significant indirect effect. Conversely, in Table 9, results show that affordability does not play the role of a mediator to any considerable level, as corroborated by a path coefficient of -0.014, a t-value of 0.872, and a p-value of 0.383, showing that affordability has no significant impact as a mediator in this context. The discussion of the current study is provided below.

5 Discussion

The study analyzed the way transport accessibility, safety perceptions, and price influence mobility among the domestic workers of the City of Johannesburg, South Africa. Utilizing SEM, the study tested direct and indirect relationships that affirmed significant findings on how these factors are interlinked in influencing commuting decision and pattern. The primary research objective was to analyze the connection between transport accessibility and safety perceptions in Johannesburg City domestic workers, South Africa. In hypothesis one, the work postulated there is a direct positive connection between transport accessibility and perceptions of safety ($\beta = 0.600, p < 0.001$) and that displays how accessible public transport systems have enhanced perceived security. This aligns with the idea that well-connected, accessible transit modes provide a feeling of security and mastery over travel choices, with reduced vulnerability to risky alternatives. This conclusion places integrated, secure transit modes at the forefront of planning accessible transport systems, supporting conclusions made by Ceccato & Paz (2017) about safety as a priority in public transport environments.

The second research question examined the effect of transport affordability and accessibility on the mobility behavior of domestic workers in the City of Johannesburg, South Africa (Hypotheses 2 and 3). Results indicate that transport accessibility significantly affects mobility behaviour ($\beta = 0.267, p < 0.001$), whereas affordability does not significantly affect ($\beta = -0.052, p = 0.352$). This reveals the logistical importance of human flow management and access coordination in urban transport planning. This also means that while accessibility is a direct determinant of mobility patterns, affordability may not be limited, possibly due to the low-income nature of domestic work, if limited options necessitate reliance on available transport modes. This corroborates studies finding that where affordable alternatives are unavailable, commuters may prefer accessibility to affordability, as noted in areas with poorly served transit routes [27]. Consequently, in areas of the city where affordable transit options are not an option, domestic workers might restrict their travel to necessity only, restricting their participation in social or leisure activities, which can lead to isolation and social exclusion by not allowing full integration into urban life.

The third research aim examined the influence of transport safety perceptions and transport accessibility on mobility behaviour among domestic workers in the City of Johannesburg, South Africa (Hypothesis 4). Results indicate that safety perceptions positively affect mobility behaviour ($\beta = 0.480, p < 0.001$), with an observation that perceived safety is critical in shaping commuter behaviour. This finding is in tandem with studies proving that safety concerns could alter modes of transport, especially for women and other marginalized groups [57]. For domestic labourers, enhanced safety perceptions could enable frequent travel despite barriers, emphasizing the need for policies to raise transit security interventions.

The fourth research objective examined the extent to which safety and affordability perceptions mediate between accessibility of transport and mobility behavior in the City of Johannesburg, South Africa (Hypotheses 6 and 7). Evidence supported that perceptions of safety mediate this relationship ($\beta = 0.287, p < 0.001$), but affordability does not exert a significant mediating effect ($\beta = -0.014, p = 0.383$). This suggests that affordable transport is not enough but relies on how perceived safety impacts on commuters. The limited bearing of affordability states that financial limits could be secondary within a setting where safety and convenience of transport matter. In the case of housemaids, transportation might exist, but it won't effectively work if security doesn't exist. Safety concerns, such as exposure to crime or harassment, have a direct bearing on how often they can commute, demonstrating the importance of safe transit zones for these kinds of workers.

6 Conclusion

This study emphasizes the critical role of transport accessibility, safety perceptions, and affordability in the mobility behaviour of domestic workers in the City of Johannesburg, South Africa. The results show that transport accessibility and safety perceptions significantly influence mobility behaviour, but affordability has a less direct influence, which can be explained by the lack of transport options resulting in the utilization of available modes regardless of financial difficulties. In South Africa, improved transport accessibility can enhance commuting and reduce "transport poverty" among domestic workers, particularly in conjunction with proper safety interventions. To fix the transport predicament of South African domestic workers, solutions should focus on enhancing accessibility, security, and affordability, particularly among the vulnerable group like women. Public education campaigns on secure travel, alongside the training of conductors and drivers in safety, can impose a safety-culture of vigilance, challenging the transportation impediments faced by low-income domestic workers and other urban commuters in South Africa. The theoretical contribution of this research to the logistics management practice is provided below.

6.1 Theoretical contributions

This study offers a theoretical contribution to research on logistics management by framing mobility patterns within the logistics flows of people, information, and cost-effective resources across urban networks. This study focused on domestic workers, an underrepresented yet central subject group in the case of urban transport studies. This study widened the application of transport equity theory in examining how equitable access to transport can minimize "transport poverty" and enable socio-economic integration. The study puts forward a model that positions perceived safety and affordability as mediators between mobility behavior and transport accessibility. This extends logistics theory by bringing to the limelight the aspect that perceived safety is not only a consequence but also a crucial mediator mediating mobility decisions and transport access, particularly for vulnerable individuals. This study contributes to the sustainable urban logistics literature by presenting the problem of "transport poverty" and defining it in terms of accessibility, affordability, and social inclusion. It echoes the findings of Tsikada, Luke and Mageto [58], who emphasise that sustainable value networks must address not only operational performance but also environmental and social dimensions, especially when designing logistics systems for vulnerable populations. It emphasized the significance of inclusive transport policy and low-cost transit measures in creating accessible, equitable logistics systems. This study explored these interdependencies that broaden theoretical discussion in logistics management to include social equity and welfare, supporting logistics models that consider the interests of marginal workers in cities. This contribution is significant in rethinking urban planning policy and operations towards both attaining economic efficiency and social impacts, hence further enhancing logistics' place as a field of study that can directly influence societal well-being and inclusivity. The applicatory ramifications of the research are discussed in the subsequent section.

6.2 Practical contributions and implications for stakeholders

This study provides recommendations for various stakeholders interested in urban transport, logistics planning, and policymaking. The results are that government regulation and public purchasing play a fundamental role in ensuring transport affordability and accessibility. Amorim, de Abreu e Silva and Gonçalves [59] investigate how public transport subsidies are distributed among different income groups and transport modes, using data from Oslo. The study shows that while high-income users (e.g. rail commuters) often receive larger passenger subsidies, the overall effect is moderately progressive since lower-income individuals rely more on buses and metro services. This urges the government and urban planners to implement policies that ensure low-income commuters, particularly domestic workers in South Africa who are heavily dependent on public transport, have affordable, accessible, and safe means of transport. Urban transport can reduce "transport poverty" and enhance greater social inclusion through the provision of targeted subsidies, increasing transit network coverage to low-density townships, and transit zone safety enhancement. Low-cost housing near centres of employment will cut travel time and enhance domestic workers' lifestyles. These findings also support a logistics-centric view where technical elements of logistics, such as transport scheduling, routing, and flow management, are critical to reducing inefficiencies in human mobility and urban service delivery. The study highlighted the role of public transport operators to upgrade reliability and safety to enhance female passengers' service perception. Initiatives such as increased vigilance and women-only compartments on public transport during peak risk hours can reduce safety concerns, making public transport a more viable and appealing means of travel. Transport operators can also turn to technological measures, such as real-time transit information via apps and SMS, to allow domestic workers to plan safer and more efficient travel. Private sector employers who depend on in-home workers can apply this research to learn about the transportation issues of their employees and help them support safe transportation plans. These can be through transport allowances, flexible working hours for coordination with public transport schedules or even providing pooled transport facilities that help maintain workers' wellness and performance. These can be applied to urban transport planning, where transport services are organized to cater to the interests of marginalized groups, including domestic workers. The last part presents the research limitations and agenda for future studies.

6.3 Limitations and future research

This study, despite its contribution regarding transportation accessibility, affordability, and safety for local workers, also has several limitations that create a research agenda to be pursued in the future. This study on domestic workers within the City of Johannesburg constrained generalisability to other urban South African cities. Hence, future research might proceed to explore commuting problems among low-paid workers across different geographical and urban-rural contexts to make comparisons to detect transport requirements in different situations. The cross-sectional data constraint the ability to follow changes over time in the patterns of commuting, possibly in response to economic or transport policy developments. Longitudinal studies would illuminate whether mobility behaviour and transport experience evolve over time because of policy or economic factors. Self-reported data from surveys include such possible response biases or recall errors for transport experience. Widening the choice of methodologies to include mixed methods, combining qualitative description with quantitative observation, would facilitate deeper exploration of individual, social, and economic factors behind transportation decision-making by domestic workers. The analysis is only considering the mediating effects of affordability and safety, but not other determinants influencing mobility choices, such as social support systems, alternative modes of transport, or economic determinants on a bigger scale like employment conditions and labour policies. Future studies could thus also consider other mediating variables to provide a broader perspective on how factors influence mobility choices. Investigating the implications of emerging transport technologies or shared mobility modes for access and safety among poor workers could inform more creative, more just, and more responsive transport planning, in service to a broader vision of social equity in urban mobility.

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The impact of road infrastructure quality and network density on road accident numbers in Poland

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Abstract: This study examines how road infrastructure quality and public road network density influence road accident numbers in Poland between 2010 and 2024. Using annual national-level data on public road density, total and upgraded hard-surfaced roads, and motorways and expressways per 10,000 inhabitants, a log-linear regression model with HAC Newey–West standard errors was applied to estimate elasticities. Results show that higher public road density slightly increases accident numbers, while a greater total length of hard-surfaced roads reduces them. Upgraded roads exhibit a positive association with accidents, suggesting potential behavioral or traffic exposure effects, whereas motorway and expressway density strongly decreases accident rates. These findings highlight the complex interplay of infrastructure quality, network expansion, and traffic exposure, providing guidance for policymakers to prioritize investments in high-standard roads while monitoring upgraded segments for safety outcomes.

1 Introduction

Road safety remains a critical public policy concern in the European Union, where traffic collisions continue to generate significant social and economic losses. Although long-term improvements in legislation, enforcement, and vehicle technology have contributed to a gradual decline in accident numbers, substantial cross-country variation persists, suggesting that structural factors such as road infrastructure quality and network density play a decisive role in shaping safety outcomes. In Poland, the last fifteen years have been characterized by intensive investment in the national road network, including the expansion of motorways and expressways, the upgrading of hard-surfaced roads, and the modernization of both urban and rural segments. At the same time, the country has experienced a systematic decrease in the number of traffic accidents, fatalities, and injuries. These parallel trends raise an important empirical question: to what extent can the improvement of the road network explain the observed decline in accident numbers?

Existing literature provides extensive evidence that infrastructure quality influences road safety through multiple mechanisms, including improved geometric design, higher pavement standards, reduced collision points, and the separation of traffic flows. Studies frequently highlight the safety benefits associated with high-standard roads such as motorways and expressways, as well as the risks associated with dense networks of lower-quality local roads. Nevertheless, empirical findings remain mixed, partly due to methodological limitations, differences in spatial units of analysis, and the scarcity of long-term national-level datasets linking detailed road characteristics with accident counts. In the Polish context, most research has examined specific infrastructure elements—such as expressway development or black-spot elimination—while comprehensive evaluations of how broader structural indicators (e.g., hard-surfaced road length, improved pavement share, and public road density) affect accident dynamics over time are still limited.

This study seeks to fill this gap by examining the relationship between road accident numbers and two key infrastructural dimensions: (1) the quality of road surfaces and (2) the density of the public road network, expressed per 10,000 inhabitants. Using annual data for Poland for the years 2010–2024, the analysis focuses exclusively on infrastructure-related determinants, isolating them from economic and behavioural factors explored in earlier research. The study employs a log-linear regression specification, allowing the estimation of elasticities that quantify how percentage changes in road network characteristics are associated with percentage changes in accident counts.

Compared to prior research by the author [1], which focused on forecasting traffic accidents using neural networks, the present study emphasizes causal links between infrastructure quality, network density, and accident numbers. By isolating structural infrastructure determinants and applying log-linear regression with HAC Newey–West standard errors, this paper provides novel evidence on how specific road improvements impact safety outcomes over a long-term national horizon.

By linking long-term accident trends with systematic improvements in road infrastructure, this article contributes new evidence to the discourse on road safety determinants in Central and Eastern Europe. The findings offer insights relevant to policymakers, particularly in the context of prioritizing investments in road modernization, balancing the expansion of local and high-standard roads, and designing infrastructure strategies aimed at further reducing accident rates in Poland.

2 Literature review

The impact of road infrastructure quality and road network density on the number of road accidents in Poland has been the subject of numerous studies. The results indicate that infrastructure quality and road type have a significant impact on the number and severity of accidents, with the highest risk occurring on two-way, two-lane roads, which have the highest proportion of fatal accidents. Infrastructure defects, such as poorly designed intersections or insufficient signage, lead to the creation of “black spots,” and analyses suggest that up to 75% of road incidents may be related to the characteristics of the infrastructure and the road environment [2-4].

At the county level, the length of the road network and transportation spending correlate with safety levels—urban counties with the highest investment spending saw the largest reduction in fatalities, although at the same time there was an increase in serious injuries. The density and structure of the road network are related to accident and fatality rates [4,5].

The quality of infrastructure, including the condition of the road surface, the presence of protective barriers and lighting, is strongly linked to the severity of accident consequences, and investments targeting the most dangerous road sections can significantly reduce the risk of fatalities. The studies use statistical models, neural networks, and spatial analyses to predict the number of accidents depending on the type of road, network density, and infrastructure quality, with motorway expansion and an increase in the number of vehicles contributing to a stabilization or increase in the number of accidents, especially on new road sections [1,6].

Various techniques for predicting the number of accidents can be found in the literature. The most popular techniques for predicting the frequency of road accidents are time series-based approaches [7,8], which have the disadvantage of often containing a residual autocorrelation component [9] and do not allow the quality of the forecast to be assessed on the basis of previous forecasts. For forecasting, Procházka et al. [10] used a multi-seasonality model, while Sunny et al. [11] used the Holt-Winters exponential smoothing technique. One of its disadvantages is that external variables cannot be added to the model [12,13].

Local analyses conducted at the city level, such as in Poznań, indicate that the intensity of development and the number of traffic lights are important predictors of the number of accidents in specific locations. In addition to infrastructure characteristics, weather conditions, traffic intensity, and sociodemographic factors are also important, as they can strengthen or weaken the impact of infrastructure on road safety [14].

This study contributes to the literature by integrating multiple dimensions of infrastructure quality and density into a unified analytical framework based on long-term national data. It systematically examines whether structural improvements in Poland’s road network correspond with measurable reductions in accident numbers [15].

3 Materials, methods and research hypotheses

Based on theory and empirical evidence, the following hypotheses are proposed:

- **H1:** Higher public road network density per 10,000 inhabitants increases the number of road accidents.
- **H2:** Greater total length of hard-surfaced roads per 10,000 inhabitants decreases accident numbers.
- **H3:** Increased length of upgraded hard-surfaced roads per 10,000 inhabitants reduces accident numbers.
- **H4:** Higher density of motorways and expressways per 10,000 inhabitants reduces accident numbers.

Annual data for Poland from 2010-2024 were obtained from the Central Statistical Office (GUS). Variables include:

- Number of road accidents (dependent variable) - NRA.
- Public road network density per 10,000 inhabitants - DEN.
- Length of hard-surfaced roads per 10,000 inhabitants - HARD.
- Length of upgraded hard-surfaced roads per 10,000 inhabitants - UPG.
- Length of motorways and expressways per 10,000 inhabitants - MOTO.

All variables are standardized per 10,000 inhabitants to account for demographic changes.

The analysis focuses exclusively on infrastructure-related factors, deliberately omitting traffic intensity, vehicle ownership, and behavioral variables. This choice is based on the availability of data at the national level throughout the study period and on the study’s objective of isolating the structural effects of infrastructure. Although the omission of these variables may introduce potential biases, it allows for a reliable estimation of the elasticity of infrastructure characteristics as the main factors influencing long-term accident trends.

A log-linear regression model was applied (1):

$$\ln(NRA_t) = \beta_0 + \beta_1 \ln(DEN_t) + \beta_2 \ln(HARD_t) + \beta_3 \ln(UPG_t) + \beta_4 \ln(MOTO_t) \quad (1)$$

where:

- NRA_t – number of road accidents in year t ,

- DEN_t – density of public roads per 10,000 inhabitants,
- $HARD_t$ – hard-surfaced roads per 10,000 inhabitants,
- UPG_t – upgraded hard-surfaced roads per 10,000 inhabitants,
- $MOTO_t$ – motorways & expressways per 10,000 inhabitants,
- β_i – coefficients representing elasticities.

Elasticities (β coefficients) represent the percentage change in accidents associated with a 1% change in each infrastructure variable. Ordinary Least Squares (OLS) with HAC Newey–West standard errors was used to address heteroskedasticity and autocorrelation.

Table 1 Statistical data from 2010-2024 [16,17]

Years	NRA	DEN	HARD	UPG	MOTO
2010	38832	113.4	83.2	77.5	1.2
2011	40131	113	82.3	76.6	1.12
2012	37062	110.7	80	74.3	1.07
2013	35847	110.5	79.1	73.4	0.97
2014	34970	109.9	78	72.2	0.89
2015	32967	109.2	75.7	69.8	0.79
2016	33664	109.3	76.6	70.7	0.83
2017	32760	108.4	74.8	68.9	0.78
2018	31674	107.8	74.1	68.2	0.71
2019	30288	106.9	72.9	67	0.63
2020	23540	105.4	71.1	64.8	0.4
2021	22816	107	72.8	66.8	0.47
2022	21322	113.8	85	79.5	1.35
2023	20936	113.2	84.1	78.5	1.29
2024	21519	112.4	84.9	79.8	1.39

4 Results

Logarithmic regression analysis revealed significant correlations between road infrastructure characteristics and the number of road accidents in Poland between 2010 and 2024. The density of the public road network (DEN) was positively correlated with the number of accidents, with an elasticity of 0.10. This means that a 1% increase in road network density per 10,000 inhabitants was associated with an increase in the number of accidents of approximately 0.1%, which partially confirms hypothesis H1.

$$\ln(NRA_t) = 7.75 + 0.1 * \ln(DEN_t) - 0.2 * \ln(HARD_t) + 0.55 * \ln(UPG_t) + 0.9 * \ln(MOTO_t)$$

Table 2 Value of coefficients

Variable	β (elasticity)	Interpretation	Statistical significance
DEN	0.10	1% increase in network density → 0.1% increase in accidents	$p < 0.05$
HARD	-0.20	1% increase in paved road length → 0.2% decrease in accidents	$p < 0.05$
UPG	0.55	1% increase in improved road length → 0.55% increase in accidents	$p < 0.05$
MOTO	-0.90	1% increase in highway density → 0.9% decrease in accidents	$p < 0.01$
Constant	7.75	—	—

The length of paved roads (HARD) showed a negative elasticity of -0.20, indicating that a 1% increase in the share of paved roads per 10,000 inhabitants led to a 0.2% decrease in the number of accidents. This result fully confirms hypothesis H2, emphasizing the important role of road surface quality in reducing the risk of accidents.

Unexpectedly, the length of upgraded roads (UPG) showed a positive elasticity of 0.55. This means that a 1% increase in the length of upgraded roads per 10,000 inhabitants was associated with a 0.55% increase in the number of accidents, which contradicts hypothesis H3. This result suggests the possibility of indirect factors, such as increased traffic or higher speeds on better quality roads.

The strongest impact was shown by the density of motorways and expressways (MOTO), with a negative elasticity of -0.90. This means that a 1% increase in the density of high-class roads per 10,000 inhabitants was associated with a 0.9% decrease in the number of accidents, which fully confirms hypothesis H4 and emphasizes the importance of high-standard roads in reducing the risk of collisions.

Overall, the results indicate that both road network density and pavement quality have a significant impact on accident dynamics, although the direction of the effects depends on the type of infrastructure and the potential influence of behavioral factors.

5 Discussion

The results corroborate the theoretical expectation that road infrastructure shapes safety outcomes, though some findings require careful interpretation. The positive association between public road density and accidents aligns with literature suggesting that denser networks increase traffic exposure, creating more potential conflict points. The negative effect of hard-surfaced road length reinforces the role of pavement quality in mitigating crash risk, particularly in rural and suburban areas where unpaved roads prevail.

The unexpected positive elasticity of upgraded roads warrants deeper examination. One possible explanation is that road upgrades attract more traffic, including higher-speed travel, which may partially offset the safety benefits of improved surfaces. This phenomenon emphasizes the need to consider behavioral responses to infrastructure improvements, as better roads may inadvertently increase accident risk if not accompanied by speed management or complementary safety measures.

This finding may reflect increased traffic exposure and higher driving speeds on newly upgraded road sections, consistent with the risk compensation hypothesis. Previous studies [18] indicate that road upgrades can temporarily elevate accident rates if drivers perceive improved conditions as safer and adjust their behavior accordingly. Additional robustness checks, such as lagged effects or interaction with traffic volume proxies, could further clarify this relationship.

The pronounced negative impact of motorways and expressways confirms findings from European contexts: high-standard roads, with controlled access and minimal intersections, are highly effective in reducing accidents. This underscores the importance of continued investment in expressway expansion and the modernization of key arterial routes to enhance national road safety.

Comparing the magnitudes of effects, motorway density exerts the largest influence, suggesting that strategic expansion of high-standard roads could yield the most substantial reductions in national accident numbers, whereas incremental changes in local network density and general pavement improvements produce more modest effects.

6 Conclusions

This study demonstrates that structural features of Poland's road network significantly affect traffic accident numbers. Key findings include:

1. Denser public road networks slightly increase accident numbers, highlighting the trade-off between connectivity and exposure.
2. The overall length of hard-surfaced roads reduces accidents, supporting the hypothesis that general road quality improves safety.
3. The positive coefficient for upgraded roads indicates that infrastructure improvements alone may not automatically reduce accidents, and traffic behavior must be considered.
4. Expansion of motorways and expressways offers the most substantial safety benefits, confirming that high-standard roads are central to accident prevention strategies.

Policymakers should prioritize a balanced approach: continue developing high-standard roads while monitoring traffic patterns on upgraded segments to ensure that safety gains are fully realized. Further research could integrate vehicle volumes, speed data, and behavioral responses to provide a more comprehensive understanding of how infrastructure improvements interact with traffic exposure to influence accident risk.

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Design and manufacture of pineapple cutting machines

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Abstract: Pineapple processing is traditionally performed manually, which is labor-intensive, inconsistent, and prone to safety risks. While industrial scale machines exist, their high cost and complexity limit accessibility for small and medium scale enterprises or household level use. This study addresses this gap by presenting the design and manufacture of a simple and low-cost pineapple cutting machine. The machine integrates peeling, quartering, and coring operations into a single stroke using a specially designed knife assembly fabricated from food-grade stainless steel. A prototype was fabricated and tested, confirming that the design meets essential requirements for cutting precision, safety, and ease of use while remaining economically feasible. The outcomes demonstrate that efficiency and consistency can be achieved without reliance on complex mechanisms, making the machine particularly suitable for small enterprises and local markets. Future work will focus on enhancing blade durability, introducing automated fruit feeding, and conducting large-scale performance evaluations.

1 Introduction

Pineapple (*Ananas comosus*) is among the most popular tropical fruits, widely consumed in both fresh and processed forms. Its sweet flavour, nutritional value, and economic importance have made it a key commodity in the global fruit market [1-5]. However, the preparation of pineapples for consumption remains a challenge due to their thick, spiny rind, fibrous flesh, and irregular geometry [6-9]. Traditionally, peeling and slicing are performed manually using knives, which is labour intensive, time consuming, and often results in inconsistent quality, high material waste, and safety risks for workers. Commercial fruit processing machines are available, but most are designed for large scale industrial applications. Such machines are often expensive, mechanically complex, and unsuitable for small and medium sized enterprises, local producers, or household level operations where processing volumes are lower and cost constraints are critical [10-15]. This creates a significant gap in the availability of affordable and user-friendly pineapple cutting solutions that balance functionality with economic feasibility. Recent research in fruit processing has introduced semi-automatic cutting and slicing machines for apples, mangoes, and melons, yet their adaptation to pineapples remains limited [16-19]. The complexity of existing designs and their high manufacturing costs restrict widespread adoption, especially in developing regions where demand for low-cost processing tools is high.

This study aims to fill that gap by designing and manufacturing a simple and low-cost pineapple cutting machine. The design emphasizes minimal mechanical complexity, low production cost, and ease of operation while maintaining acceptable levels of cutting precision and hygiene. To achieve this, lightweight aluminium extrusions are used for the structural frame, food-grade stainless steel for the cutting components, and a straightforward vertical cutting mechanism for ease of fabrication and maintenance.

Unlike existing industrial pineapple processing machines, this design provides a simple, low-cost solution suitable for small enterprises and household applications. The proposed machine provides a practical solution for small-scale pineapple processing, offering reduced manual effort, safer operation, and improved consistency at a fraction of the cost of commercial machines. The outcomes of this work demonstrate that simplicity and affordability can be achieved without compromising basic functionality, making the design suitable for small enterprises, local markets, and household applications.

2 Materials and methods

2.1 Design requirements

The development of the pineapple cutting machine was guided by a set of functional and technical requirements intended to ensure practicality, safety, and affordability. Unlike large-scale industrial machines, the target application of this research focuses on small- and medium-scale enterprises and local processing units, where simplicity of design and low manufacturing cost are critical factors. From a functional perspective, the machine was required to reliably process pineapples with diameters ranging from 70–120 mm, reflecting the common size variation encountered in local markets [10,20–22]. The design was expected to deliver cutting uniformity with minimal waste, thereby improving yield compared to manual operations. A processing capacity of at least 50 pineapples per hour was identified as an acceptable benchmark to justify the transition from manual to semi-automated processing. In terms of safety and ergonomics, the machine was required to minimize operator effort and reduce the risk of injury associated with manual knife usage. Operation had to be intuitive and feasible without specialized training, thereby ensuring accessibility for small-scale users. With respect to materials and hygiene, all food-contact components were specified to be manufactured from stainless steel or other food-grade materials to comply with sanitary standards. The structural frame was required to be lightweight, durable, and easy to assemble, with preference for modular construction that could be fabricated using widely available workshop equipment. Finally, the economic constraint constituted a central design requirement. The overall construction had to rely on low cost, locally available materials and standard manufacturing processes, ensuring that the prototype could be replicated in resource-limited environments. The emphasis on affordability was intended to make the technology accessible to small enterprises and household-level users, distinguishing it from high-cost industrial solutions.

2.2 Design process

The operation of the pineapple cutting machine is based on a simple vertical cutting mechanism (Figure 1). The pineapple is placed manually on the table, which serves as the supporting surface during cutting. The cutting unit consists of cylindrical stainless-steel knives mounted centrally in the frame. These knives are responsible for slicing through the pineapple rind and flesh to achieve uniform separation. The vertical movement of the knives is achieved through a lead screw mechanism, which converts rotary motion into precise linear motion.

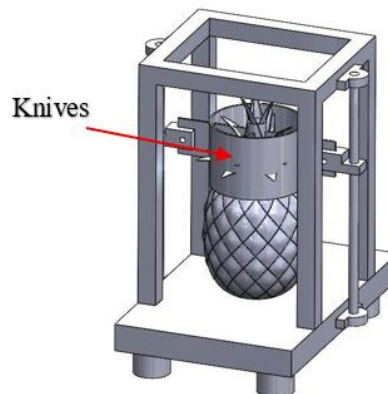


Figure 1 3D CAD model of the proposed pineapple cutting machine

As the lead screw rotates, the knife assembly moves smoothly along the vertical axis (Z-axis), ensuring stable and controlled cutting. This design eliminates the need for complex guiding rails and minimizes overall cost while maintaining functional reliability. During operation, the fruit remains stationary on the table, and the cutting unit performs the downward stroke. Once the cut is complete, the knives are retracted upward for removal of the processed fruit and preparation for the next cycle. This arrangement reduces operator effort, improves safety compared to manual knife handling, and ensures consistent cutting thickness.

The knife moves vertically by a lead screw, the torque required at the screw is (1):

$$T = \frac{F_c d_m}{2} \left(\frac{l + \pi \mu d_m}{\pi d_m - \mu l} \right) \quad (1)$$

where T is the torque required at the screw (N·m), F_c is the axial cutting force (N), d_m is the mean diameter of the lead screw (m), l is the lead of the screw (m), and μ represents the coefficient of friction between the screw and the nut.

This relationship accounts for both the mechanical advantage of the screw geometry and the frictional resistance inherent in the transmission system. By calculating the required torque, the stepper motor and belt–pulley drive system

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can be properly sized to ensure smooth, stable, and efficient operation. Incorporating this analysis into the design phase guarantees that the chosen drive components provide sufficient capacity while avoiding unnecessary oversizing, which would increase cost and complexity.

The motor rotates the lead screw, causing the knife unit to descend along the vertical axis. As the knives move downward, they first penetrate and peel the outer skin of the pineapple, then continue to slice the fruit into four equal sections, while simultaneously separating the central core. Once the knives reach the table surface, a lower travel switch is triggered. This switch provides feedback to the controller, which immediately reverses the motor current, causing the lead screw to rotate in the opposite direction. The knives are then retracted upward along the same path. When the knife unit reaches the upper limit of its motion, it activates the second travel switch, which sends a stop signal to the controller, thereby terminating the cutting cycle. At this point, the pineapple has been fully peeled, segmented, and cored, and the machine is ready for the next operation. This working principle ensures consistent performance while maintaining a low-cost design, as it relies on a stepper motor, simple lead screw transmission, and basic on/off limit switches rather than complex sensors or high-cost control systems.



Figure 2 Cutting mechanism design

The cutting unit of the machine was designed to perform multiple functions simultaneously: peeling the outer skin, segmenting the fruit into four equal sections, and separating the central core (Figure 2). The design integrates three main cutting elements into a single assembly:

Outer Circular Blade – A stainless-steel ring-shaped knife designed to penetrate the tough outer rind and peel the pineapple skin uniformly. Its geometry ensures that the fruit surface is cut along the circumference in a single downward stroke.

Radial Cross Blades – Two orthogonal blades arranged perpendicularly across the diameter of the circular knife. These blades divide the pineapple into four equal quarters during the cutting process, ensuring uniform segmentation.

Inner Cylindrical Core Knife – A smaller circular knife positioned at the center of the assembly. This blade is responsible for extracting the fibrous pineapple core, producing a clean cylindrical cut that separates the edible fruit from the inedible center.

The cutting force required to slice through pineapple skin can be approximated as (2):

$$F_c = \tau \cdot A \quad (2)$$

where F_c is the cutting force (N), τ represents the shear strength of the pineapple skin and flesh (N/m²), and A denotes the cross-sectional cutting area of the blade (m²). This formulation provides the baseline force needed by the knife unit, which directly influences the selection of the stepper motor and the lead screw transmission system. By ensuring that the motor torque capacity exceeds the calculated cutting force requirements, the design maintains both reliability and efficiency while adhering to the low-cost objective of the machine.

The entire knife assembly is mounted on the lead screw-driven vertical motion system, which enables simultaneous cutting, peeling, quartering, and coring in one cycle. This integrated blade arrangement significantly reduces processing time compared to conventional multi-step cutting operations.

The knives were modeled in CAD to verify geometric compatibility with pineapples ranging from 70–120 mm in diameter and to optimize the alignment of the cutting edges. All cutting components were fabricated from food-grade stainless steel (AISI 304) to ensure sharpness, durability, and compliance with hygiene requirements.

2.3 Finite element analysis

To ensure the structural integrity and functional reliability of the proposed pineapple cutting machine, a finite element analysis (FEA) was conducted on the key mechanical components. The primary objective of this analysis was to evaluate stress distribution and deformation under cutting loads, rather than to pursue complex optimization, in accordance with the simple and low-cost design philosophy of the machine.

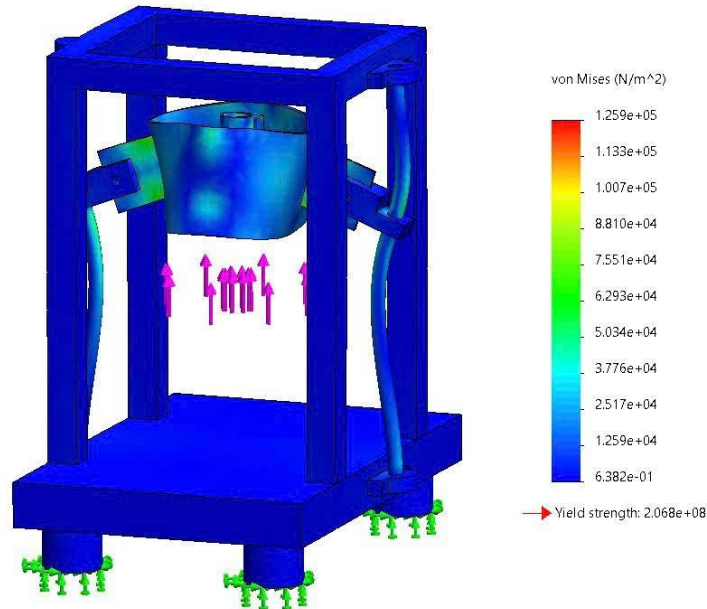


Figure 3 Von Mises stress distribution under axial cutting load

Figure 3 illustrates the von Mises stress distribution obtained from the simulation. The results show that the maximum stress occurs locally in the knife and its supporting brackets, which is consistent with the expected load path during cutting. The peak von Mises stress remains significantly lower than the yield strength of the stainless steel material, indicating a sufficient safety margin against plastic deformation. The frame structure exhibits low stress levels and negligible deformation, confirming adequate rigidity and structural stability.

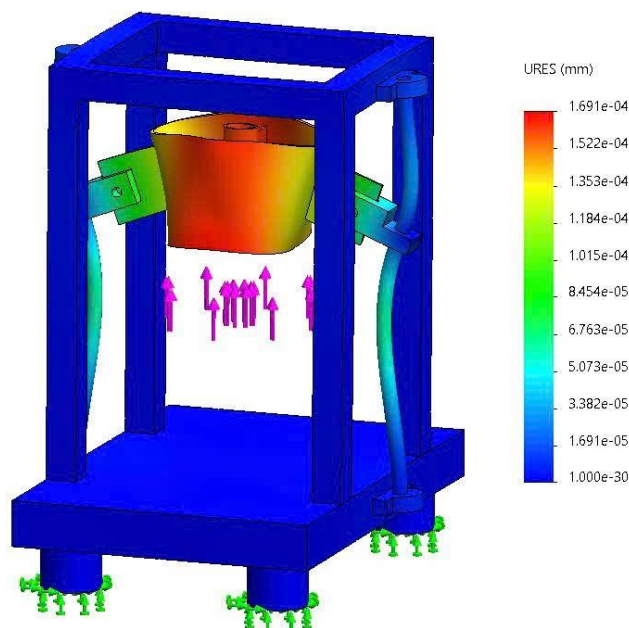


Figure 4 The total displacement (URES) distribution of the pineapple cutting machine

In addition to stress evaluation, the total displacement response of the machine was examined to assess structural stiffness and alignment stability during operation. Figure 4 presents the contour plot of the resultant displacement (URES) under the same axial cutting load and boundary conditions applied in the stress analysis.

The maximum displacement is observed at the knife assembly, which is directly subjected to the cutting force, while the supporting frame exhibits minimal deformation. The peak displacement magnitude remains on the order of 10^{-4} mm, indicating that elastic deformation is extremely small relative to the overall dimensions of the machine. Such a low displacement level confirms that the structural frame provides sufficient rigidity to maintain alignment between the knife assembly and the working table throughout the cutting cycle.

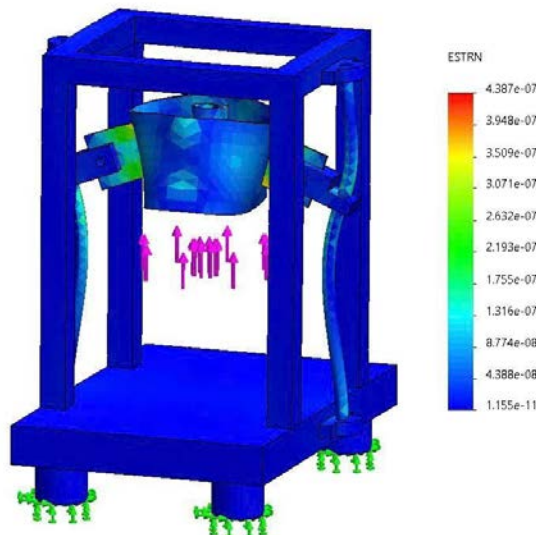


Figure 5 the equivalent strain (ESTRN) distribution of the pineapple cutting machine

Figure 5 illustrates the equivalent strain (ESTRN) contours of the pineapple cutting machine subjected to the axial cutting load.

The strain distribution follows a pattern consistent with the stress results, with higher strain concentrations localized around the knife assembly and its immediate supporting brackets, where the cutting load is directly applied. In contrast, the structural frame exhibits very low strain levels, indicating that the deformation remains within the elastic range throughout the system. The maximum equivalent strain is on the order of 10^{-7} , which is significantly below the elastic limit of the materials used.

3 Results and discussion

The mechanical performance of the proposed pineapple cutting machine was evaluated using finite element analysis and analytical estimation of operational parameters. The numerical results confirm that the structure operates safely under representative cutting loads. The maximum von Mises stress in the knife assembly remains far below the yield strength of stainless steel (AISI 304), while the total displacement and equivalent strain are on the order of 10^{-4} mm and 10^{-7} , respectively. These values indicate negligible elastic deformation, ensuring stable alignment between the cutting unit and the working table during operation.

Based on the validated structural rigidity, the operational performance was estimated from the kinematics of the lead screw system. Using a stroke length of approximately 220 mm, a lead screw lead of 8 mm/rev, and a conservative stepper motor speed of 100-120 rpm, the total cutting cycle time was estimated to be 30-40 s per fruit. This corresponds to a practical throughput of approximately 45-80 fruits/h when manual loading and unloading are considered, which is appropriate for small-scale processing applications.

Cutting accuracy and repeatability were assessed through mechanical tolerance analysis. Since the knife geometry is fixed and structural deformation is negligible, cutting precision is governed primarily by blade design rather than frame compliance. The guided vertical motion enables consistent peeling, quartering, and coring, with an estimated segmentation deviation within $\pm 1-2$ mm. Material loss was estimated to be 8-12%, which is lower and more consistent than typical manual cutting (15-25%) reported in the literature.

A photograph of the assembled prototype is shown in Figure 5, confirming the feasibility of the proposed design and the correspondence between the CAD model and the manufactured system. Compared with manual cutting, the proposed machine reduces operator effort, improves safety by limiting direct contact with cutting edges, and provides more uniform cutting outcomes. Although the system does not match the throughput of industrial machines, its simplicity, low cost, and

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adequate performance make it well suited for small enterprises and household-level users. The main limitations include manual fruit loading, sensitivity to irregular fruit shapes, and blade wear over extended operation, which will be addressed in future developments.



Figure 6 Assembled prototype of the pineapple cutting machine

4 Conclusions

This study successfully designed, analyzed, and fabricated a mechanical prototype of a robotic platform intended for plant care applications in agriculture. By focusing exclusively on mechanical architecture, the project established a robust and modular frame constructed from 6063-T5 aluminum profiles, combined with a 6 mm thick 6061-T6 aluminum plate for load distribution. Key mechanical subsystems, including a differential drive system with chain transmission and a compact wheelbase, were developed to support operation in structured environments such as greenhouses and narrow crop rows. Finite Element Analysis (FEA) confirmed the structural integrity of the design under operational loads, with stress and strain levels significantly below the yield limits of the materials used. The physical prototype was assembled using accessible manufacturing techniques and materials, validating the design's manufacturability, rigidity, and ease of assembly.

Building upon the successful development of the mechanical prototype, future work will focus on transforming the platform into a fully autonomous and intelligent agricultural robot. This includes integrating sensor systems such as soil moisture sensors, ultrasonic or LiDAR modules, and environmental monitors to enable real-time interaction with crop conditions. A control system based on microcontrollers (e.g., Arduino or Raspberry Pi) will be implemented to manage motor control, process sensor data, and execute plant care routines. In addition, the robot's navigation capabilities will be enhanced through the application of GPS, vision-based tracking, or predefined path planning to ensure precise movement within crop rows or greenhouse environments. Modular end-effectors for watering, spraying, and crop monitoring will also be designed for quick attachment and task flexibility. Finally, efforts will be made to improve energy efficiency and sustainability, including exploring the use of solar panels for outdoor operation. These advancements aim to transform the current mechanical platform into a smart, adaptable, and scalable solution for modern agriculture.

This study presented the design and manufacture of a simple and low-cost pineapple cutting machine aimed at addressing the limitations of manual processing and the high cost of industrial-scale equipment. The machine integrates peeling, quartering, and coring operations into a single downward stroke through a specially designed knife assembly. The incorporation of an Arduino-controlled stepper motor and lead screw mechanism ensured precise vertical motion, while

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the use of aluminum profiles, stainless-steel blades, and HDPE components demonstrated that the machine could be fabricated using locally available materials and standard workshop processes.

The prototype validated the feasibility of the proposed design, confirming that essential performance requirements—such as functionality, structural stability, and ease of use—could be achieved without reliance on complex or expensive subsystems. The results highlight the potential of the machine to improve efficiency, reduce operator effort, and provide consistent cutting outcomes, thereby making it suitable for small enterprises, local markets, and household-level applications.

Future work will focus on extending the functionality and improving the durability of the system. Specific directions include:

- Developing an automatic feeding and positioning system to further reduce manual intervention.
- Investigating advanced blade materials and coatings to enhance cutting efficiency and minimize wear.
- Introducing adjustable cutting dimensions to accommodate different fruit sizes and consumer preferences.
- Conducting large-scale performance testing, including statistical evaluation of cutting quality, throughput, and reliability.
- Exploring the integration of low-cost sensing modules for improved process monitoring and safety assurance.

Through these improvements, the proposed design has the potential to evolve from a prototype into a practical tool for wider adoption in pineapple processing, particularly in resource-limited contexts where affordability and simplicity are critical.

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Technological solution for improving productivity and efficiency in manufacturing processes

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Keywords: wood-processing industry, technological modernization, drying technology, productivity, energy efficiency.
Abstract: The aim of this paper is to evaluate the impact of technological modernization on productivity, efficiency, and energy performance of manufacturing processes. In wood-processing production, the drying operation represents a critical technological stage due to its high time and energy demands. The applied methodology is based on a comparative case study approach. It includes technical, productivity, efficiency, and economic assessments of the existing drying technology and the proposed modern automated drying kiln. Productivity was evaluated as production output per unit of time, while efficiency was assessed using specific energy consumption per unit of dried lumber volume. The analysis was conducted using operational data obtained directly from the manufacturing environment. The results confirm that the modernization of drying technology leads to a significant reduction in drying cycle duration, enabling higher throughput and increased productivity without additional labour input. The modernization resulted in a productivity increase of up to 45% and a reduction in specific energy consumption of up to 25%. The economic evaluation demonstrates that productivity growth and energy savings create favourable conditions for reducing unit production costs and improving capacity utilisation. The findings indicate that targeted technological modernization of key production operations represents an effective tool for increasing productivity and efficiency in wood-processing manufacturing and provides a practical basis for investment decision-making and process optimisation.

1 Introduction

The wood-processing industry plays a strategically important role in economic development, as it transforms renewable raw materials into products with high added value [1,2]. However, despite the ecological benefits of wood, its limited availability and long regeneration period require companies to adopt a sustainable approach to resource utilisation and continuously improve operational efficiency in order to remain competitive [3,4].

Increasing global demand for wood-based products places continuous pressure on manufacturing companies to enhance productivity while reducing costs and environmental impacts [3]. Labour productivity represents a key indicator influencing production performance and business sustainability in the wood industry [5].

Recent research highlights that modernization of technological equipment is a fundamental prerequisite for eliminating production bottlenecks and ensuring stable output [6,7]. The implementation of automated control systems contributes not only to higher operational efficiency but also to reduced material waste and improved quality consistency [8,9]. Technological innovations therefore support sustainable economic growth by increasing process flexibility and reducing energy intensity in manufacturing.

Industrial enterprises operating in dynamic market environments must continuously optimise their production systems to remain competitive. Productivity represents the relationship between input resources and achieved outputs, while efficiency reflects the degree to which managerial and operational objectives are achieved in manufacturing enterprises.

In the wood-processing industry, productivity is significantly influenced by production planning, technological equipment, material flow organisation, workforce qualification, and the level of technological losses. Timber drying is recognised as one of the most time-intensive and energy-demanding operations in wood-processing manufacturing and

significantly affects production lead time and overall throughput. Inefficient drying technology may result in low throughput, increased operating costs, quality deviations, and delays in order fulfilment.

To achieve higher performance indicators, modernization of key production technologies is essential. The implementation of advanced drying systems contributes not only to shortening the production cycle but also to improving mechanical stability, dimensional accuracy, and the commercial value of final products.

Based on the need to optimise productivity and efficiency in the production process, the aim of this paper is to evaluate the impact of drying technology modernization on productivity, energy efficiency, and economic performance under real industrial conditions. The study focuses on the replacement of outdated drying technology with an advanced automated system designed to support faster processing, more stable operating conditions, and reduced energy consumption.

2 Methodology

The research was conducted in a real wood-processing manufacturing enterprise focused on the production of coniferous timber products. The study applies a case study approach aimed at evaluating the impact of technological modernization on productivity, efficiency, and energy performance of the drying operation.

The methodological framework consisted of six consecutive steps. The first step involved an analysis of the current production system, with a focus on the drying operation as a critical bottleneck influencing production throughput, energy consumption, and product quality. The second step focused on the technical characterisation of the existing drying kiln, including capacity, drying cycle duration, operating temperature, installed power, and the level of process automation. Operational data were obtained from production records and direct observations. The third step consisted of proposing a modern drying technology represented by an automated Mühlböck drying kiln equipped with an intelligent K5 control system. The proposed technology was analysed based on manufacturer specifications and projected operational parameters. The fourth step involved a comparative evaluation of productivity, expressed as production output per unit of time. Productivity was assessed by comparing the number of drying cycles and processed lumber volume under identical time conditions before and after modernization. The evaluation focused on the reduction of drying cycle duration and the resulting increase in throughput. The fifth step focused on efficiency and energy evaluation based on the relationship between output volume and energy input. Energy efficiency was assessed using specific energy consumption per cubic metre of dried lumber ($\text{kWh}\cdot\text{m}^{-3}$), taking into account improvements in thermal insulation, air circulation, and automated process control. The final step involved an economic assessment of the modernization proposal, including a comparison of operating conditions and justification of the investment from a techno-economic perspective. The evaluation was based on real enterprise data and standard economic indicators commonly applied in industrial practice.

All quantitative data used in the analysis were derived from actual production conditions documented in the enterprise records and from calculations performed within the framework of the associated diploma thesis. Compared to the diploma thesis, this paper extends the analysis by introducing a structured quantitative evaluation framework combining productivity, energy efficiency, and economic indicators under consistent operational assumptions. The performance parameters of the proposed drying technology were derived from manufacturer-provided technical specifications and design documentation, enabling a direct comparison of the current and proposed technological solutions [10].

3 Results and discussion

3.1 Technical comparison of drying technologies

Drying represents one of the most time-consuming and energy-intensive technological operations in wood-processing manufacturing. Its performance significantly influences production throughput, operational costs, and product quality. The existing drying kiln used in the analysed enterprise is based on hydrothermal wood treatment and manual or semi-automatic process control. Although the kiln remains operational, its performance is limited by outdated control mechanisms, longer drying cycles, and higher thermal losses.

The proposed technological solution involves the replacement of the existing system with a modern Mühlböck drying kiln equipped with an intelligent K5 control system. The modernization introduces a higher level of automation, improved air circulation, enhanced thermal insulation, and optimised heat recovery. These technical improvements directly influence drying cycle duration, process stability, and energy utilisation. The K5 control system enables automated regulation of temperature, humidity, and airflow parameters throughout the drying process. The main functional architecture of the control and monitoring system is illustrated in Figure 1.



Figure 1 Mühlböck K5 automatic control and monitoring system [11]

To enable a quantitative comparison, Table 1 presents selected technical parameters of the current and proposed drying technologies.

Table 1 Technical comparison of current and proposed drying kilns (Source: own processing)

Parameter	Current	Proposed
Chamber capacity (m ³)	120	120 + 120
Drying time for spruce (h)	135 – 270	67 – 202
Drying time for fir (h)	192 – 384	96 – 288
Final moisture content (%)	80 → 10	80 → 10
Max. chamber temp. (°C)	70	95
Installed power (kW)	400	500 + 500

The comparison shows that the proposed solution enables the parallel operation of two drying chambers with a capacity of 120 m³ each, resulting in an increase in the total installed drying capacity to 240 m³. However, the increase in productivity is not achieved solely by expanding the drying capacity through parallel chamber operation, but also by shortening drying cycles and optimising process parameters due to a higher level of automation.

3.2 Productivity evaluation

Productivity in the drying process was evaluated as the ratio between production output and processing time. In accordance with the applied methodology, productivity was expressed as the volume of dried lumber processed per unit of time (1):

$$P = \frac{Q}{t} \quad (1)$$

where:

P is productivity (m³·h⁻¹),

Q is the volume of dried lumber (m³),

t is the total drying time (h).

For productivity evaluation, the production output Q was defined as the total volume of lumber processed by all drying chambers operating in parallel during one drying cycle.

Productivity growth results from the combined effect of parallel chamber operation and a significant reduction in drying cycle duration achieved through technological modernization and a higher level of process automation.

The modernization of the drying technology results in a substantial reduction in drying cycle duration. For spruce lumber, the drying time decreases from 135–270 h to 67–202 h, while for fir lumber the cycle duration is reduced from 192–384 h to 96–288 h. This reduction enables a higher number of drying cycles to be completed within the same operational time frame.

Productivity growth is primarily achieved through a reduction in technological waiting time and an increased number of processed batches per unit of time. Based on comparative calculations performed under identical operational conditions, the modernization of the drying technology resulted in a productivity increase of approximately 30–45 %, depending on the wood species and the applied drying regime. The reported percentage values represent interval values derived from a comparison of minimum and maximum drying regimes for individual wood species. These improvements are mainly associated with a reduction in drying cycle duration of approximately 35–50 %, which enables a higher number of drying cycles to be completed within the same operational time frame without additional labour input.

3.3 Efficiency and energy evaluation

The installed power of the drying equipment represents an indicative technical parameter and does not reflect the actual energy consumption, which depends on the drying process conditions, load level, and the degree of process control.

The efficiency of the drying process was evaluated with respect to energy consumption and the utilisation of input resources. In accordance with industrial practice, efficiency was assessed as the ratio between achieved output and energy input required for the drying operation. For comparative purposes, the evaluation focused on specific energy consumption per unit of dried lumber volume.

Energy efficiency was expressed using the following relationship (2):

$$E = \frac{Q}{E_n} \quad (2)$$

where:

E is energy efficiency ($\text{m}^3 \cdot \text{kWh}^{-1}$),

Q is the volume of dried lumber (m^3),

E_n is the total energy consumption during the drying cycle (kWh).

For improved clarity and comparability of results, specific energy consumption was also applied as an inverse indicator (3):

$$SEC = \frac{E_n}{Q} \quad (3)$$

where:

SEC is specific energy consumption ($\text{kWh} \cdot \text{m}^{-3}$),

E_n is the total energy consumption during the drying cycle (kWh),

Q is the volume of dried lumber (m^3).

The existing drying kiln exhibits relatively high specific energy consumption due to outdated thermal insulation, limited heat recovery, and less efficient air circulation. These factors lead to higher heat losses and increased energy demand per drying cycle. In addition, manual or semi-automatic control limits the ability to continuously optimise process parameters in response to actual wood moisture conditions.

The proposed Mühlböck drying kiln achieves higher energy efficiency through improved thermal insulation, optimised airflow distribution, and an intelligent K5 control system enabling continuous process regulation. These features reduce unnecessary energy losses and stabilise drying conditions throughout the cycle.

Comparative analysis indicates that the proposed drying technology leads to a reduction in specific energy consumption of approximately 15–25% per cubic metre of dried lumber. At the same time, the stabilisation of drying parameters contributes to lower technological waste, reduced risk of material defects, and improved consistency of final moisture content.

The reduction in specific energy consumption is not achieved solely by shortening the drying time, but primarily through optimisation of thermal management, improved process control, and stabilisation of drying conditions.

The achieved improvement in energy efficiency directly supports overall process efficiency by lowering operating costs and reducing the energy intensity of production. The results confirm that technological modernization of the drying

operation has a positive impact not only on productivity but also on sustainable resource utilisation and operational efficiency.

3.4 Economic evaluation of the modernization proposal

In addition to technical and energy-related benefits, the proposed modernization of the drying technology was also evaluated from an economic perspective. The economic assessment focuses on the justification of the investment by considering operating conditions, productivity gains, and efficiency improvements achieved through the implementation of the modern drying kiln.

The replacement of the existing drying kiln with the proposed Mühlböck technology requires an initial capital investment associated with the acquisition of new equipment and its installation. However, this investment is accompanied by measurable operational benefits resulting from shorter drying cycles, increased throughput, and reduced energy consumption.

From an economic perspective, the modernization results in a reduction of energy-related operating costs by approximately 15–25%, corresponding to the decrease in specific energy consumption.

In addition, increased productivity contributes to a reduction in unit production costs by approximately 20–30 %, primarily due to improved capacity utilisation and shorter processing time per production batch. These combined effects significantly enhance the economic performance of the drying operation and justify the investment from a long-term operational perspective.

Improved automation and process control also contribute to more stable operation, reducing the likelihood of unplanned downtime and technological losses. As a result, the drying process operates closer to optimal conditions, improving cost efficiency throughout the entire production cycle.

Based on a comparison of the current and proposed technological solutions under identical operational assumptions, the economic evaluation confirms that the modernization of the drying technology represents a rational investment. The combined effects of productivity growth, energy savings, and improved process stability create favourable conditions for long-term cost reduction and increased competitiveness of the manufacturing enterprise. Under the assumption of maintaining comparable operating conditions and production volumes, the proposed modernization can be considered economically justified.

4 Conclusion

Improving productivity and efficiency is a fundamental prerequisite for maintaining competitiveness in contemporary manufacturing environments. In wood-processing production, the drying operation represents a critical technological stage that significantly influences production throughput, energy consumption, and final product quality.

This study evaluated the impact of drying technology modernization on productivity, energy efficiency, and economic performance under real industrial conditions. The results indicate that the modernization of the drying process leads to a productivity increase of up to 45% and a reduction in specific energy consumption of up to 25%.

The replacement of outdated drying technology with a modern automated Mühlböck drying kiln resulted in a substantial reduction in drying cycle duration, enabling a higher number of processed batches within the same operational time. As a result, the productivity of the drying process was significantly increased without additional labour input or an extension of working hours.

The analysis further confirmed that technological modernization contributes to improved energy efficiency through reduced specific energy consumption per unit of dried lumber. Enhanced thermal insulation, optimised air circulation, and intelligent process control enable more stable drying conditions. As a result, energy losses and technological waste are reduced, supporting sustainable resource utilisation and overall process efficiency.

From an economic perspective, the modernization of the drying technology represents a justified investment. Productivity growth, energy savings, and improved process stability contribute to lower unit production costs and better utilisation of installed production capacity. The combined technical and economic effects strengthen the competitiveness of the manufacturing enterprise and create favourable conditions for long-term operational optimisation.

The findings confirm that targeted technological modernization of key production operations represents an effective instrument for increasing productivity and efficiency in wood-processing manufacturing. The applied evaluation methodology and achieved results provide a practical basis for investment decision-making and process optimisation in similar industrial environments.

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Applications of IDMA technology in US Patents

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Abstract: Interleave Division Multiple Access (IDMA) is a promising multiple access technique for wireless communication systems because of its potential to enhance spectral efficiency, mitigate interference, and support reliable multi-user transmission. This paper presents the fundamental principles of IDMA, with emphasis on user-specific interleaving, symbol mapping onto available time slots, and the corresponding deinterleaving and recovery process at the receiver. The main advantages of IDMA are discussed, including improved spectral efficiency, better error performance, lower implementation complexity, flexibility for diverse wireless environments, and increased communication security through user-specific interleaver sequences. In addition to the theoretical overview, the paper reviews selected United States patents related to IDMA and closely associated non-orthogonal multiple access approaches published between 2020 and 2025. The analysed patents cover a wide range of applications, including narrowband machine-type communication, random access procedures, asynchronous coded multiple access combined with OFDM, wireless network control, storage systems, and joint transmissions in shared wireless resources. The review demonstrates that IDMA principles continue to be adapted and extended in response to the evolving requirements of modern wireless communication technologies. The examined patent activity confirms the ongoing technological relevance of IDMA and related multiple access schemes and highlights their potential for efficient, scalable, and interference-resilient communication in advanced wireless networks.

1 Introduction

The available frequency spectrum and time slots are shared by users of the IDMA multiple access scheme. To distribute the data symbols across the available time slots, each user in IDMA is given a distinct interleaver sequence. Through the reduction of multipath fading and interference, this procedure aids in enhancing the communication system's performance.

Interleavers of various kinds, such as block, convolutional, and turbo interleavers, can be used to implement IDMA. The system's particular needs and the intended performance determine the type of interleaver to use. Block interleavers are the most basic kind of interleavers, whereas turbo interleavers are the most intricate.

1.1 Working principles

The fundamental idea behind IDMA is to interleave the data symbols throughout the time slots that are available. To distribute the data symbols over the available time slots, each user is given a distinct interleaver sequence. The interleaving process disperses the data symbols over a longer time span, which lessens the effects of interference and multipath fading.

IDMA's interleaving procedure (see Fig. 1) includes the subsequent steps:

1. Data Symbol Generation: The transmitter creates data symbols.
2. Interleaving: A distinct interleaved sequence that is assigned to every user is used to interleave the data symbols.
3. Mapping: The available time slots are mapped onto the interleaved data symbols.
4. Transmission: The wireless channel is used to send the mapped data symbols.

At the recipient (refer to Figure 1), the original data symbols are recovered using the inverse procedure. The inverse interleaver sequence that is assigned to each user is used to deinterleave the received data symbols after they have been demapped from the time slots. The original data is then recovered using the demodulated data symbols.

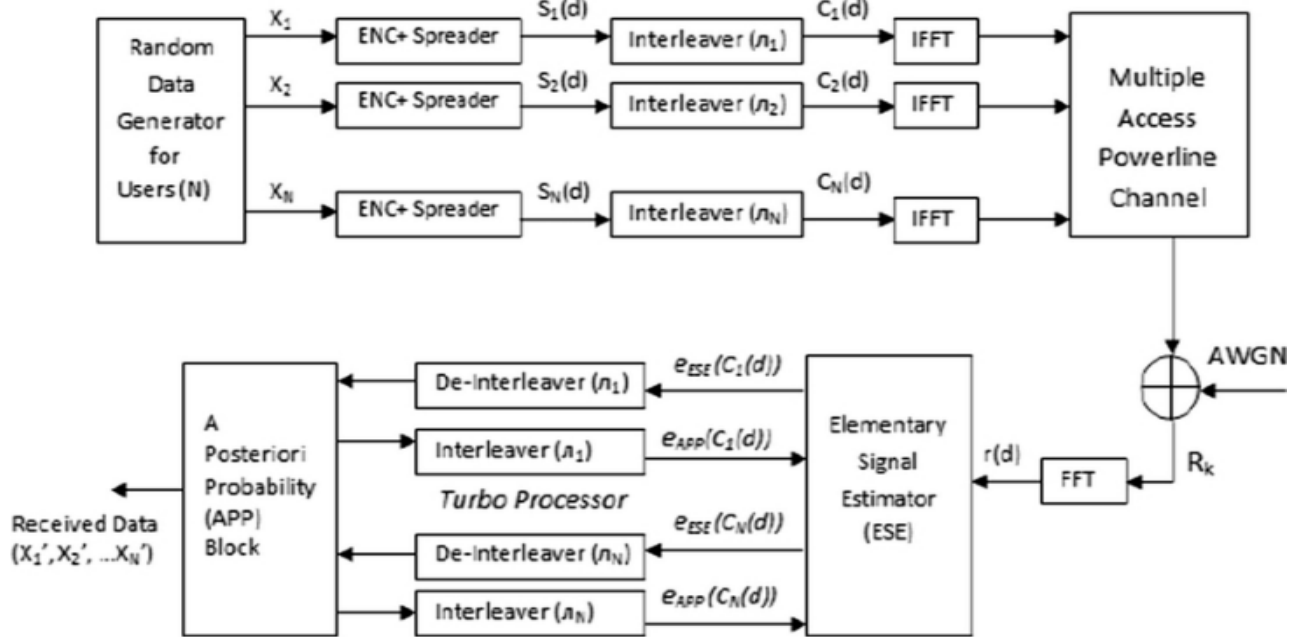


Figure 1 IDMA block diagram

1.2 Advantages of IDMA

Compared to other multiple access schemes, IDMA offers the following benefits:

- 1-Improved Spectral Efficiency: By effectively utilizing the available frequency spectrum and time slots, IDMA can offer higher spectral efficiency than other multiple access schemes, like CDMA and TDMA.
2. Better Error Performance: By lessening the effects of interference and multipath fading, IDMA can offer better error performance.
3. Low Complexity: Compared to other schemes like CDMA, IDMA is a straightforward and effective multiple access scheme that requires less sophisticated hardware and processing.
- 4-Flexibility: IDMA is an adaptable multiple access scheme that works well in a variety of wireless communication settings and uses.
5. Security: By employing distinct interleaver sequences for every user, IDMA can enhance security by making it more difficult for unauthorized users to gain access to the network.

1.3 Applications of IDMA

IDMA has a number of potential uses in wireless communication systems, such as:

- 1-Mobile Communication Systems: IDMA can be used to enhance network performance and coverage in mobile communication systems like 3G, 4G, and 5G.
2. Satellite Communication Systems: To increase transmission efficiency and lessen the effects of multipath fading and interference, satellite communication systems can employ IDMA.
3. Wireless Sensor Networks: IDMA can be applied to wireless sensor networks to enhance network performance and energy efficiency.

2 Applications of IDMA in US Patents

The deployment of Internet of Things (IoT) interconnected devices where one or more user equipment is configured for uplink transmission with one or more uplink time-frequency regions for enhanced Machine Type Communication Non-Orthogonal Multiple Access uses an uplink non-orthogonal multiple access for narrowband machine type communication in [1]. A demodulation reference signal cyclic shift assignment, orthogonal cover code assignment, interleaver assignment, starting subframe periodicity, starting subframe offset, time duration in each period, and one or more signal thresholds are defined and signaled as part of the configuration.

The present disclosure in [2] pertains to a communication system that supports higher data rates than 4.sup.th-generation (4G) systems, such as Long Term Evolution (LTE), and is either pre-5 .sup.th-generation (5G) or 5G. The current disclosure pertains to the technical area of wireless communication, specifically to a random access method. The process involves sending a random access signal along with a payload from a terminal to a base station. The preamble sequence is set randomly or based on the size of the data to be sent, and the payload is set up based on the current service requirements. The terminal then receives feedback information that is sent back by the base station and corresponds to

the random access signal. This feedback information includes at least one of the following: timing advance information, uplink transmission grant information, acknowledgement, and unique user identification information. By designing the random access signal so that it includes both the payload and the preamble sequence, the current solution can reduce access delay in data transmission by using two interactive steps to realize the function that is realized through four interactive steps in the prior art.

Numerous innovative ideas and plans related to non-orthogonal multiple access for wireless communications are explained in [3]. In order to decrease multi-user interference (MUI) and enhance performance, a group orthogonal coded access (GOCA) scheme is implemented. To distinguish user equipment (UEs) based on distinct patterns of repetition, a repetition division multiple access (RDMA) scheme is implemented. To lower MUI and boost efficiency, a low-density spreading (LDS) scheme is implemented.

The non-orthogonal multiple access method described in the patent in [4] is accomplished by: choosing a physical resource at random to perform non-orthogonal multiple access among the predefined areas of contention-based data transmission; choosing a reference signal sequence for a contention-based data transmission through the chosen physical resource; choosing a contention resource for the contention-based data transmission; choosing a scrambling sequence to be applied to data transmission in the contention-based data transmission; and transmitting a data channel that contains data and a reference signal corresponding to the chosen reference signal sequence through the chosen physical resource, where the data channel is transmitted by permitting the chosen scrambling sequence to be applied thereto.

In [5], a user's equipment and technique for using Asynchronous Coded Multiple Access (ACMA) in a communication system that uses Orthogonal Frequency Division Multiplexing (OFDM) to transmit a random-access radio frequency (RF) signal are described. A burst with symbols is created by performing an inverse fast Fourier transform on a unique word (UW) multiplexed with the payload; each burst symbol is transmitted in synchrony with successive symbol-start instants; and an information stream is encoded as OFDM symbols using a low rate Forward Error Correction (FEC) coding appropriate for Successive Interference Cancellation (SIC) to form a payload. Within a subset of consecutive symbol-start instants of the burst, the UW contains multiple Zadoff-Chu (ZC)-like sequences. A receiver looks for consecutive ZC-like sequences to identify burst arrival. The UW with an extra ZC-like sequence can be used to estimate the channel state.

The electronic device and method for interleaved multiple access communication are disclosed in [6]. The processing circuit of an electronic device for an interleaved multiple access control terminal is set up to gather information about interleaved multiple access communication between a transmitting and receiving apparatus; determine configuration parameters for the transmitting apparatus based on the information; and provide the determined configuration parameters to the transmitting apparatus so that the transmitting apparatus is configured with the transmitting parameters for communicating with the receiving apparatus. These parameters include the operation parameters of an interleaver of the transmitting apparatus, which is used to distinguish the transmitting apparatus from other transmitting apparatus.

A method and a device for uplink data transmission using a non-orthogonal code multiple access scheme in a wireless communication system are provided by the patent in [7]. In particular, a base station provides information to a terminal on a codebook unique to that terminal. The codebook for a predetermined multi-dimensional modulation contains the terminal-specific codebook. The terminal creates a complex vector by encoding an information bit using multi-dimensional modulation based on the terminal-specific codebook. In order to produce a frequency signal, the terminal applies DFT to the complex vector using the codebook unique to the terminal. Uplink data produced by applying IFFT to the frequency signal is transmitted by the terminal.

A transmitter can perform channel coding on a bit sequence to determine a coded sequence in [8]. A multiple access method, a multiple access transmitter, and a multiple access receiver. The technique also entails interleaving and/or scrambling the coded sequence, modulating the interleaved and/or scrambled sequence using a multidimensional constellation, grid mapping the modulated symbol sequence to identify a mapped sequence, and then transmitting the mapped sequence. The technique also entails a receiver receiving mixed signals from several transmitters. Each transmitter performs interleaving, scrambling, multidimensional constellation modulation, and grid mapping on the data to produce the mixed signals. The technique also involves the receiver decoding mixed information based on grid mapping pattern information, multidimensional constellation information, and interleaver and/or scrambler information.

In a wireless communication system, an apparatus serves multiple user devices in [9]. Using a non-orthogonal multiple access, or NOMA, scheme, the apparatus transmits and receives a first data signal of the first user equipment and a second data signal of the second user equipment in order to transmit and receive data of a plurality of user equipments, including at least a first user equipment and a second user equipment, on resources shared by the plurality of user equipments. Prior to the first and second data signals being superposed, they are modulated using distinct waveforms.

An electronic device and method for a wireless communication network node and an electric device and method for a wireless communication network control end are included in the current disclosure in [10]. A processing circuit is part of the electronic equipment for the wireless communication network control end. Within a predefined domain, the processing circuit can decide how to divide wireless communication transmission resources, which are then used for a network node's

initial transmission and subsequent transmissions, respectively. Additionally, the processing circuit can produce configuration data that includes details about how the wireless communication transmission resources are divided up.

Each storage controller in [11] is made up of a first storage unit, an interface unit, and a processing unit that communicates a parameter to the interface unit that directs the writing of data in each of n-number of other storage controllers (where n is a natural number of two or more). After receiving the parameter, the interface unit performs the following operations: obtaining the data from the first storage unit and storing it in the second storage unit; creating n-number of requests to write the data to each of the other storage controllers; storing each of the generated requests in n-number of queues that correspond to each of the other storage controllers; processing each request placed in each queue; and moving the data from the second storage unit to each of the other storage controllers.

The apparatus described in [12] consists of an acquisition unit that obtains an information block created from transmission data for a user and is subjected to error correction coding, as well as an interleaving unit that uses a user-specific interleaver to interleave a bit sequence of the information block. By interleaving each of the two or more partial sequences derived from the bit sequence, the interleaving unit interleaves the bit sequence.

A first and a second transmitter are part of a wireless communication system in [13]. The first transmitter is set up for a superimposed non-orthogonal multiple access, or NOMA, which allows the transmission or reception of a first data signal of the first user equipment and a second data signal of the second user equipment on resources shared by the first and second user equipment. The second transmitter is set up for a superimposed non-orthogonal multiple access, or NOMA, which allows the transmission or reception of a third data signal of the first user equipment and a fourth data signal of the second user equipment.

3 Summary and conclusion

All things considered, IDMA is a promising technology with a lot of potential advantages in the wireless communication space. As wireless communication systems develop further, IDMA might play a bigger role in enhancing network effectiveness and performance.

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Implementation of robotic workstations in internal enterprise logistics: analysis of efficiency, safety, and economic benefits in the context of Industry 4.0

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Abstract: The article addresses the implementation of robotic workstations in internal logistics with the aim of analysing the impact of automation on the efficiency of logistics processes and identifying key factors for the successful deployment of robotic systems. Contemporary logistics processes face increasing demands for flexibility, speed, accuracy, and cost reduction, while traditional material handling and transport methods based on manual labour often result in higher error rates, inefficient use of the workforce, and increased risk of occupational injuries. In the context of digitalisation and the Industry 4.0 concept, it is therefore necessary to reassess existing practices and adopt intelligent automated solutions. The research is based on the analysis of existing implementations of robotic systems in industrial enterprises and on evaluating their benefits in terms of productivity, safety, and economic efficiency. The study examines technologies such as automated storage systems, robotic manipulators, autonomous mobile robots (AMR), and automated guided vehicles (AGV), including their integration into existing logistics processes. The results indicate a significant increase in the performance and reliability of internal transport, a reduction in operating costs and material handling errors, and improvements in workplace safety. At the same time, the main barriers to implementation are identified, including investment intensity and the need for organisational changes. The article provides recommendations for the effective integration of robotic technologies aimed at enhancing the competitiveness and sustainability of industrial enterprises.

1 Introduction

The rapid development of automation and digitalisation has significantly transformed industrial production and logistics systems. Internal logistics, which ensures the flow of materials, components, and information within enterprises, is increasingly recognised as a critical factor influencing productivity, responsiveness, and operational efficiency. Traditional material handling systems based on manual labour are often characterised by limited flexibility, higher error rates, and increased safety risks, which makes them less suitable for highly dynamic production environments [1]. As a result, companies are increasingly adopting robotic and automated solutions to enhance efficiency and reliability.

The concept of Industry 4.0 has accelerated the integration of intelligent technologies into logistics systems, emphasising cyber-physical systems, real-time data exchange, and autonomous decision-making processes [2]. Within this framework, automated guided vehicles (AGVs) and autonomous mobile robots (AMRs) have become essential tools for optimising internal transport, enabling continuous material flow and reducing dependency on human operators [3]. Research shows that robotic transport systems can significantly reduce throughput times and increase operational stability, particularly in high-volume production environments [4].

Automated storage and retrieval systems (AS/RS) and robotic manipulators also play a key role in improving warehouse performance and order-picking accuracy [5]. Studies indicate that the integration of robotic handling technologies contributes to higher inventory accuracy, reduced labour costs, and improved workplace ergonomics [6]. Furthermore, simulation-based analyses demonstrate that the implementation of robotic workstations can enhance system throughput while minimising bottlenecks in production logistics [7].

Despite these advantages, the adoption of robotic solutions in internal logistics remains associated with several challenges. High initial investment costs, integration complexity, and the need for organisational change management are frequently identified as major barriers to implementation [8]. Moreover, successful deployment requires not only technological readiness but also process redesign and workforce adaptation [9]. Human-robot collaboration models are therefore increasingly explored as a means of balancing automation with operator flexibility and maintaining system resilience [10].

Recent studies also highlight the importance of data-driven optimisation and digital twins in evaluating the performance of automated logistics systems before their physical implementation [11]. Such approaches enable enterprises to predict economic returns, identify risks, and optimise system configuration, thereby improving investment decision-making [12]. In addition, safety analyses confirm that robotic systems can significantly reduce accident rates when properly integrated into logistics processes and supported by adequate control strategies [13].

Overall, the literature indicates that robotic workstations represent a promising pathway toward more efficient, reliable, and sustainable internal logistics systems. However, their successful implementation requires a comprehensive assessment of technical, economic, and organisational factors, as well as a systematic approach to integration within existing production environments.

2 Methodology

2.1 Definition of problem

Company ALFA s.r.o. specialises in the production of printed circuit boards (PCBs) (Figure 1), which represent a fundamental component of most electronic devices. The production system consists of several interconnected departments, including material receiving, surface-mount technology (SMT) assembly, soldering, optical inspection, and packaging. Efficient coordination between these units is essential to ensure continuous production flow, short lead times, and consistent product quality. However, the current internal material handling system is based exclusively on manual transport performed by workers using pallet trucks and platform carts, which has proven to be increasingly inadequate for the operational demands of modern electronics manufacturing. Similar limitations of manual material handling in high-mix electronics production environments have been identified in several industrial logistics studies [14].



Figure 1 Printed circuit boards (PCB) [15]

One of the most critical bottlenecks occurs at the SMT assembly line, where delays in the delivery of components lead to machine downtime. Interruptions in material supply reduce utilisation of high-value equipment and negatively affect production stability. Research confirms that insufficiently synchronised internal logistics is a common cause of production losses in automated manufacturing systems [16]. Similar inefficiencies arise in the transfer of assembled boards to inspection stations, where limited transport capacity may result in the accumulation of semi-finished products and missed delivery deadlines.

Manual transport also introduces quality and safety risks. Improper handling may lead to mechanical damage to sensitive electronic components or mixing of batches, resulting in rework and additional operational costs. Furthermore, the system is highly dependent on human resources, meaning that staff shortages or shift fluctuations directly influence logistics performance. Such dependence on manual transport has been shown to significantly reduce system robustness and scalability in industrial production environments [9].

Additional inefficiencies are linked to suboptimal warehouse navigation and the absence of transport prioritisation mechanisms, which increases handling time and reduces material flow transparency. At the same time, labour costs associated with internal transport remain substantial while competing enterprises increasingly adopt automated logistics solutions to improve efficiency and responsiveness.

Given these limitations, the current transport system cannot respond dynamically to real-time production requirements. This creates a need for a more automated and responsive solution. One potential approach involves the use of aerial transport supported by lightweight, protective transport containers designed for safe PCB handling. Such containers combine electrostatic protection, structural rigidity, and low weight, enabling safe automated transport while maintaining product integrity (Figure 2).



Figure 2 ESD euro crates with hinged lids [17]

2.2 Technical conditions of implementation

Based on the analysis of the current internal logistics system, a concept for implementing autonomous aerial drones was proposed as an alternative to manual transport of materials and semi-finished products within the production facility. The concept builds on the premise that modern smart factories increasingly utilise vertical space and cyber-physical logistics solutions to improve transport efficiency and reduce congestion in ground-level material flows [18]. The use of ceiling space for automated transport represents a promising approach, particularly in environments where floor routes are already saturated with operators, carts, and equipment.

The proposed drone transport system is intended for deployment in the main production hall, which represents the most transport-intensive area of the facility. The hall covers approximately 400 m² and accommodates the primary logistics flows between the warehouse, SMT assembly line, quality control stations, and shipping area. The spatial parameters of the hall (20 m × 20 m, ceiling height 5.5 m) enable the establishment of a dedicated flight corridor at 2.5–3.5 m above the working zone, ensuring safe coexistence of aerial transport with ongoing production activities. Research on indoor UAV logistics confirms that separation of operational layers significantly reduces collision risks and improves system reliability [19].

The digital and physical infrastructure of the hall already meets key requirements for autonomous drone deployment. Full Wi-Fi coverage, stable environmental conditions, and sufficient lighting create suitable conditions for visual navigation and sensor-based localisation. Planned charging stations located near the warehouse and dispatch zone will enable continuous operation of a small drone fleet. Such infrastructure integration is consistent with current approaches to intelligent intralogistics systems, where real-time communication and automated task scheduling are essential for ensuring efficient material flow [20].

From a logistics perspective, the production system generates approximately 130-150 transport cycles per day, associated with an output of around 3,000 PCBs daily. Manual transport currently requires 6.5-8.5 labour hours per day, indicating substantial potential for automation. Autonomous drones are expected to reduce transport time per route by up to 50%, while also minimising handling risks for sensitive electronic components through stabilised payload holders and controlled motion. Furthermore, aerial transport allows a physical separation of traffic layers, which improves workplace safety and reduces congestion in narrow aisles.

The broader facility layout also supports drone-based integration. The main production hall is connected to a central warehouse occupying approximately 400 m² with multi-level shelving. Limited manoeuvring space within this warehouse restricts the efficiency of ground-based automated vehicles, further strengthening the suitability of aerial transport solutions. The proposed system therefore represents not only a technological upgrade but also a spatially optimised logistics concept capable of enhancing efficiency, traceability, and operational flexibility of internal material flows.

Table 1 Costs for the current situation [own processing]

Number of workers providing transport	4 workers
Monthly personnel costs for transportation	4,400 €
Annual personnel costs for transportation	52,800 €
Average number of forms of transport per day	130
Average length of one transport	3 minutes
Average daily workload of workers for transportation	6.5 hours per day

Table 2 Cost comparison: drones vs. employees [own processing]

Initial investment costs	30,000 €	0 €
Annual operating costs	2,000 €	52,800 €
Estimated annual cost savings after implementation	50,800 €	-
Number of transports per day	150+	max. 130
Reliability	high	fluctuating (human factor)
Transport speed	20 – 40 seconds	2 – 4 minutes
Risks	technical failure	fatigue, errors, absence
Safety	predictable	variable

From the above data (Table 1, Table 2), the current system cannot effectively serve production needs. Dependence on employees, time losses, delays and the risk of component damage led to increased costs, lower efficiency and losses. Implementing drone transport can achieve:

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- Significant cost reduction (savings of up to €50,000 per year),
- Faster and more predictable material movement,
- Better traceability and safety,
- Eliminating dependence on human resources at critical points.

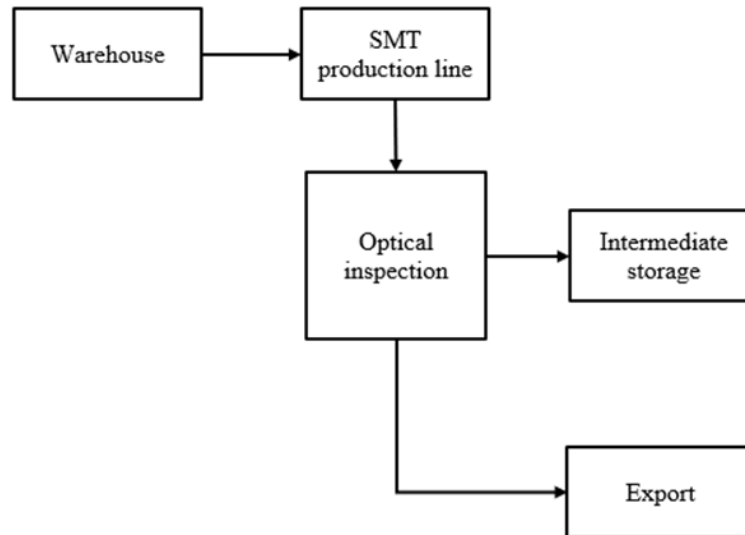


Figure 3 Current floor plan of the operation [own processing]

The methodological approach applied in this study follows a structured engineering framework consisting of five sequential steps: (1) analysis of the current internal logistics system, including data collection on transport flows, time consumption, and error rates; (2) identification of critical inefficiencies and technological limitations; (3) design of an innovative technological solution based on autonomous aerial transport; (4) technical and economic evaluation of the proposed system, including cost modelling and performance estimation; and (5) validation through comparison of key operational indicators before and after implementation. This methodology reflects standard approaches used in industrial engineering and technology design, where data-driven analysis is combined with simulation and system modelling to optimise logistics processes (Figure 3).

3 Implementation of the solution

Based on the analysis of material flows within the ALFA s.r.o. production hall, a concept for deploying a fleet of four autonomous indoor drones is proposed to ensure regular transport of materials between five key workstations: the warehouse, SMT assembly line, optical inspection, intermediate storage, and dispatch area. The operational model is designed as rotational, with two drones actively performing transport tasks while the remaining two remain in charging or standby mode (Table 3). Such redundancy-oriented fleet management is consistent with current approaches to autonomous logistics systems, where reliability and operational continuity are critical design criteria [21].

Table 3 Drone parameters [own processing]

Max. load capacity	5 kg
Dimensions	approx. 60 × 60 × 30 cm
Flight height	2 – 3.5 m above floor level
Navigation	visual (optical sensors) + QR points and routes on the floor
Navigation accuracy	±10 cm
Safety features	motion detection, automatic stop, software limits for height and route
Average transport time	20 – 40 seconds per section
Flight speed	1 – 2 m/s (taking into account safety near workers)
Number of transports	per day min. 150
Battery life approx.	2 – 15 minutes
Charging	Automatic charging in two docking stations (warehouse + expedition)
Control system	Central route planning, fleet monitoring, reporting

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Table 4 Drone maintenance costs [own processing]

Price of 1 drone	6,000 €
Price of the complete fleet (4 drones) including integration and software	30,000 €
Annual operating costs (maintenance, software updates, service)	2,000 €
Expected system life	5 years
After writing off the initial investment, the annual savings compared to manual transport are approximately 50,800 €	

The proposed solution introduces several technological and engineering innovations in the design of internal logistics systems. First, aerial transport significantly reduces transport time, with estimated transfer durations of 20–40 seconds compared to 2–4 minutes for manual handling. Studies on autonomous aerial logistics indicate that vertical transport layers can substantially increase throughput and reduce congestion in industrial facilities [22]. Second, sensitive electronic components are transported in stabilised holders, which minimises vibration-induced damage and handling errors. This aligns with findings that controlled robotic transport improves product integrity and reduces defect rates in electronics manufacturing logistics [23].

From a safety perspective, the drones operate in a dedicated height zone outside the reach of operators and ground vehicles. Equipped with obstacle detection sensors, emergency landing protocols, and predefined flight corridors, the system ensures safe coexistence with human workers. Modern indoor UAV systems commonly incorporate such layered safety architectures to meet industrial deployment requirements [24].

The technical configuration includes industrial indoor drones with payload capacities of up to 5 kg, combining optical positioning, QR-based localisation, LiDAR sensing, and inertial navigation to achieve centimetre-level positioning accuracy without GPS (Table 3, Table 4). Charging is ensured via automated docking stations placed near logistics nodes, enabling uninterrupted operation through rotational battery management. A central control platform manages task allocation, route optimisation, battery monitoring, and integration with manufacturing execution and warehouse systems, supporting real-time decision-making and traceability of material flows. The selected solution builds on commercially validated technologies, including systems deployed in logistics operations by companies such as IKEA and DSV. The drone platform chosen for the implementation is supplied by Verity AG (Figure 4), known for indoor autonomous inventory and transport solutions. Fleet coordination and automated docking are supported by the FlytWare control system developed by FlytBase, which enables scalable deployment and centralised fleet management.



Figure 4 An example of an industrial drone, from Verity AG, which will be added to the ALFA warehouse [25]

Through this configuration, the proposed system establishes the technological and organisational foundation for autonomous intralogistics based on aerial transport, emphasising operational efficiency, safety, and future scalability of the logistics infrastructure.

3.1 Expected benefits

The comparison of operational indicators (Figure 5) demonstrates not only a quantitative improvement but also a structural transformation of the internal logistics system. The reduction in transport time and increase in transport frequency indicate a shift from a labour-dependent system toward a capacity-stabilised and process-driven logistics model. Moreover, the observed cost reduction is not solely a result of workforce substitution but reflects improved utilisation of logistics resources and reduced process variability.

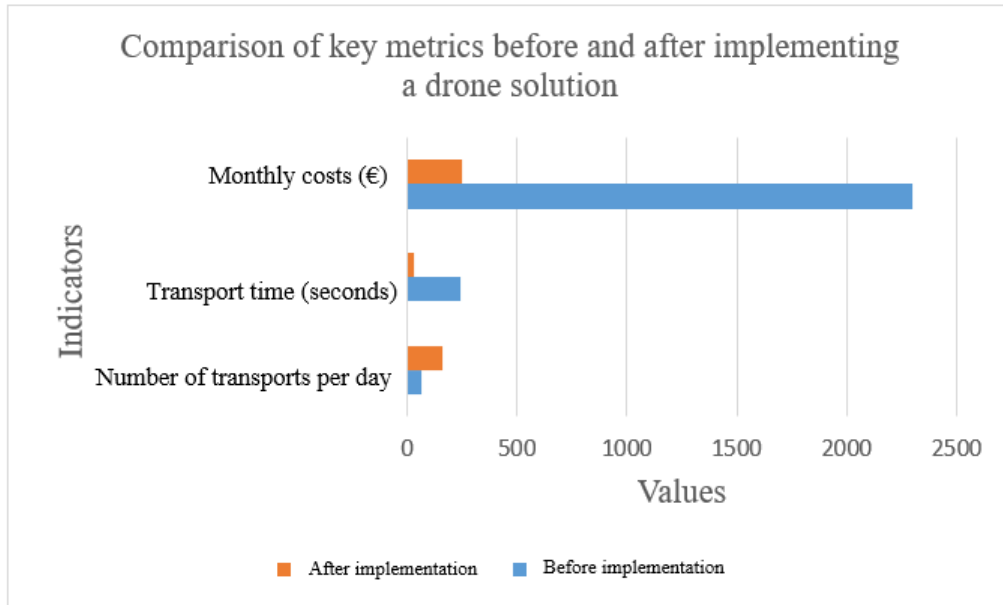


Figure 5 Comparison of operational indicators before and after drone implementation [own processing]

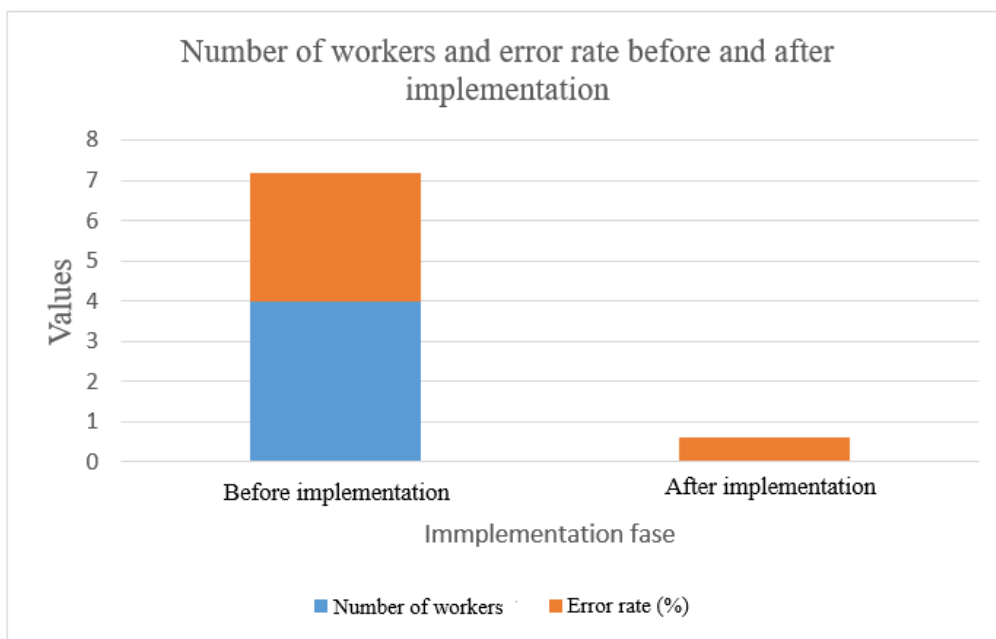


Figure 6 Change in the number of workers and error rates in transportation before and after the implementation of drones [own processing]

The reduction in error rate from approximately 3% to below 1% (Figure 6) suggests a significant improvement in process reliability, which can be attributed to the elimination of human-related variability in handling operations. The robotic transport systems in electronics manufacturing reduce defect occurrence primarily through standardisation of movement and minimisation of uncontrolled interactions with sensitive components. From a systems perspective, this improvement contributes not only to quality enhancement but also to the reduction of hidden costs associated with rework and production interruptions.

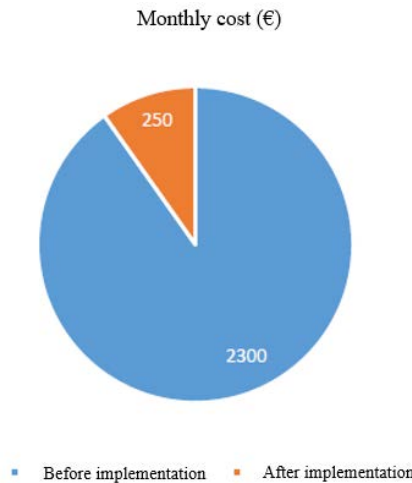


Figure 7 Reduction in labour costs after implementing drone transportation [own processing]

Figure 7 shows a comparison of monthly labour costs before and after the implementation of drone transport. The graph shows a significant reduction in labour costs due to the reduction in the need for human service.

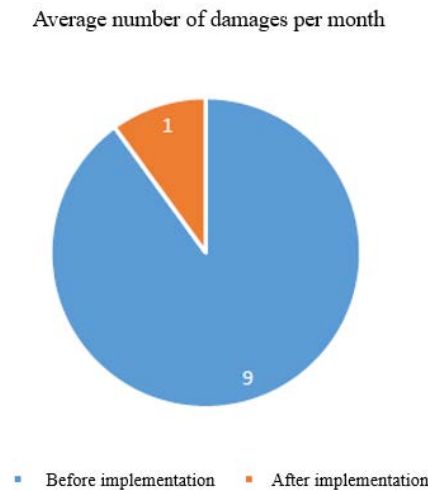


Figure 8 Reducing material damage during handling [own processing]

The decrease in material damage from an average of nine to one incident per month (Figure 8) represents a substantial improvement in handling quality. This reduction can be analytically linked to the controlled transport environment provided by drones, where predefined trajectories and stabilised payload systems minimise mechanical shocks. Similar effects have been observed in automated intralogistics systems, where the standardisation of transport conditions directly correlates with lower defect rates [23]. Importantly, this improvement has a multiplicative economic impact, as it reduces both direct material losses and indirect costs related to quality control and customer dissatisfaction.

4 Results and discussion

The implementation of autonomous drones for internal material transport at ALFA s.r.o. represents a technological intervention whose effectiveness depends on a structured deployment strategy and continuous evaluation. The implementation process was therefore divided into five phases, each producing measurable outputs that enable both technical validation and organisational adaptation.

Phase 1: System Analysis and Design

The initial phase focused on a detailed audit of internal transport processes, including measurements of transport frequency, duration, and error rates. Such data-driven assessment is essential for successful automation projects, as empirical process mapping has been shown to significantly improve the design accuracy of autonomous logistics systems [26]. The resulting technical documentation defined drone specifications, docking infrastructure, digital architecture, and

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safe aerial corridors. This structured design approach corresponds with best practices in cyber-physical production systems, where early integration of hardware and software requirements reduces later deployment risks [27].

Phase 2: Pilot Operation and Testing

A limited pilot deployment using one or two drones enabled verification of navigation precision, delivery reliability, and interaction safety with personnel. Experimental studies on indoor UAV logistics indicate that pilot testing significantly reduces operational uncertainty and improves path-planning algorithms through real-environment calibration [19]. The pilot phase provided quantitative performance indicators and enabled optimisation of flight routes and localisation markers before scaling the system.

Phase 3: Employee Training

Successful automation depends not only on technical performance but also on human–system integration. Training employees in system monitoring, emergency procedures, and maintenance improves acceptance and operational reliability. Research on human-robot collaboration confirms that structured workforce preparation reduces resistance to automation and improves safety outcomes [28].

Phase 4: Full Implementation

Following successful validation, the full fleet deployment enabled integration with enterprise and warehouse systems, providing real-time monitoring of material flows. Digital tracking of logistics operations improves transparency and decision-making efficiency, particularly when integrated with manufacturing information systems [29]. Continuous logging of transport activities also supports predictive maintenance and performance benchmarking.

Phase 5: Operational Evaluation and Optimisation

The final phase focuses on long-term data analysis, route adjustments, maintenance scheduling, and scalability planning. Continuous optimisation is widely recognised as a core element of intelligent logistics systems, where feedback loops enhance reliability and return on investment over time [30].

4.1 Discussion of quantified benefits

The quantified benefits of the proposed drone system extend beyond simple time and cost savings and indicate a broader transformation of the internal logistics performance structure. The reduction of transport time from approximately three minutes to thirty seconds represents a nearly sixfold acceleration, which significantly improves production synchronisation and reduces the probability of machine idle time. Synchronisation is a critical factor influencing overall system throughput in automated manufacturing environments.

Furthermore, the reduction in labour dependency enhances system robustness by eliminating fluctuations associated with human availability, fatigue, and variability in task execution. This observation corresponds with the findings of [9], who identify workforce dependency as a key limitation of traditional logistics systems. The introduction of autonomous drones therefore not only improves efficiency but also increases predictability, which is essential for stable production planning. From an operational perspective, the system also introduces a new dimension of spatial optimisation by utilising vertical transport layers. This approach reduces congestion in ground-level logistics flows, a benefit highlighted in recent studies on UAV-based intralogistics systems [22]. As a result, the proposed solution contributes to both micro-level process improvements and macro-level optimisation of the production environment. From a broader technological perspective, the presented results confirm a growing trend in industrial logistics toward the integration of autonomous and cyber-physical systems. While previous studies have primarily focused on ground-based technologies such as AGVs and AMRs [3,9], the findings of this research extend the current knowledge by demonstrating the practical applicability of aerial transport systems in production environments with limited spatial capacity. This complements the work [22], highlight the untapped potential of UAV-based logistics in industrial applications.

Furthermore, compared to traditional automation approaches, the proposed solution introduces a higher level of system flexibility and scalability, which are key characteristics of modern Industry 4.0 technologies. In this context, the results contribute to the ongoing discussion on the role of technological innovation in enhancing production efficiency, supporting the argument that advanced transport technologies are not only operational tools but also strategic enablers of industrial competitiveness.

5 Conclusions

The research presented in this study demonstrates that the integration of autonomous aerial transport into internal production logistics represents a viable and effective pathway toward increasing operational efficiency in electronics manufacturing environments [31]. The analysis of the existing transport system in ALFA s.r.o. confirmed that manual handling of materials and semi-finished PCB products creates measurable inefficiencies manifested in transport delays, labour dependency, inconsistent material flow, and elevated risks of product damage. These findings are consistent with broader industrial observations that identify internal logistics as a critical bottleneck in high-precision manufacturing systems [32,33].

The proposed implementation of an autonomous drone-based transport system, supported by industrial solutions such as those developed by Verity AG and coordinated through fleet-management platforms similar to FlytBase, provides a

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technologically feasible response to these challenges. The designed model demonstrated clear performance improvements, most notably a reduction in transport cycle time from approximately 3–4 minutes to less than one minute. Such acceleration directly contributes to the minimisation of machine idle time and the stabilisation of production throughput, which are recognised determinants of manufacturing productivity in automated environments [34].

From an economic perspective, the results indicate a substantial potential reduction in labour-related logistics costs, exceeding 50% compared with the current manual system. Beyond direct savings, the system enhances cost predictability and operational resilience by reducing dependence on human availability and mitigating disruptions caused by workforce fluctuations. These outcomes reinforce existing research highlighting automation as a key driver of sustainable productivity growth in Industry 4.0-oriented enterprises [35].

Quality and safety benefits further strengthen the case for implementation. Controlled aerial transport with stabilised holders and predefined flight paths reduces the likelihood of mechanical shocks, mishandling, or component misplacement. This contributes to lower defect rates, reduced rework, and improved reliability of production output. Simultaneously, the removal of repetitive manual transport tasks reduces physical strain on workers and lowers occupational risk exposure, aligning with contemporary ergonomic and safety standards in smart factories [35].

Importantly, the proposed solution is not limited to isolated process optimisation but represents a scalable step toward comprehensive digital logistics integration. The system architecture allows future expansion through interoperability with AGV platforms, robotic handling systems, or digital production monitoring tools. Such compatibility ensures that the proposed approach supports long-term strategic transformation rather than a short-term technological upgrade.

In summary, the conducted research confirms that autonomous drone transport can significantly enhance the speed, reliability, safety, and economic efficiency of internal logistics in PCB manufacturing. The proposed implementation demonstrates strong alignment with modern trends in intelligent automation and digital manufacturing, offering a realistic pathway for companies seeking to strengthen competitiveness while improving operational sustainability.

From the perspective of technological development, the proposed solution represents an advanced application of autonomous systems within industrial engineering and production logistics (Figure 9). The integration of aerial transport technologies demonstrates how innovative technological design can enhance traditional manufacturing systems and contribute to the evolution of smart factories. This approach aligns with current trends in Industry 4.0, where the convergence of automation, digitalisation, and intelligent control systems forms the basis of next-generation industrial technologies.

These findings not only confirm the practical benefits of drone-based logistics but also contribute to the existing body of research by demonstrating the applicability of aerial transport systems in high-precision electronics manufacturing, a domain that has been only partially explored in current literature.

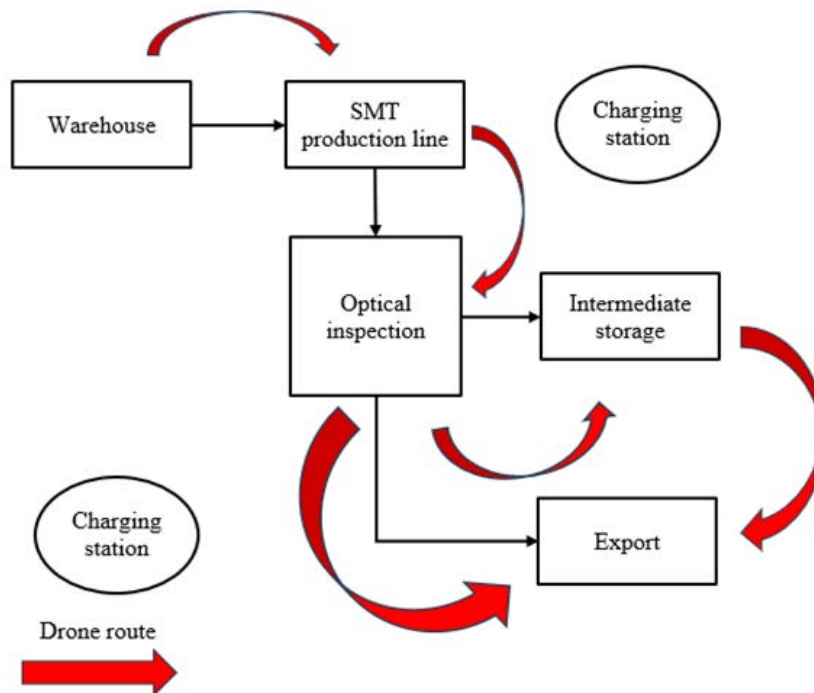


Figure 9 Floor plan of the room after the implementation solution [own processing]

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6G technology: the time has come

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Abstract: The sixth generation of wireless communication technology, or 6G technology, was created to replace 5G. Compared to its predecessors, it promises much faster speeds, more capacity, and reduced latency, opening up new applications and advancing a number of industries. Terabits per second (Tbps) is the target data rate for 6G, which is substantially faster than 5G's gigabits per second (Gbps). In order to facilitate real-time applications and instantaneous data transfer, 6G aims for nearly zero latency, possibly as low as the microsecond level. Compared to 5G's 1 million connected devices per square kilometer, 6G will allow for a potentially 10 million more. With the help of AI and machine learning, 6G will be able to manage resources intelligently, perform better, and add new features. It is anticipated that 6G will facilitate developments in fields such as imaging, location awareness, presence technology, and the Internet of Things (IoT). A review of earlier work is presented in this paper.

1 Introduction

Sixth-generation wireless (6G) is a communication protocol for wireless technologies that may offer lower latency and higher capacity than 5G. It may be able to achieve communication with a latency of one microsecond, which is 1,000 times faster than the estimated latency of 5G cellular technology, which is one millisecond. It is anticipated to be 5G mobile networks' replacement.

6G is currently being researched. Although scientific advances are experimenting with devices capable of operating at higher frequencies, the required high transmission speeds, the energy consumption rates, and the acceptable proportions of the related heat development in the electronic circuits are just some examples of the challenges 6G networks will face in the future. Studies estimate that 6G networks would likely operate in frequencies from 100 GHz to 3 THz due to their wide swaths of the unexplored spectrum (unused frequency waves in the electromagnetic spectrum). An anticipated 1,000-fold speedup over 5G is a communication protocol for wireless communications technologies that facilitate cellular data networks. Consistent connectivity and increased coverage are guaranteed by seamless integration with satellite, Wi-Fi, and fiber optics, particularly in rural regions.

With a potential latency of one microsecond, 6G is a wireless technology communication protocol that could offer higher capacity and lower latency than 5G. This is 1,000 times faster than the estimated 5G cellular technology latency of one millisecond throughput. It is anticipated to be 5G mobile networks' replacement. 6G research is still ongoing. The necessary high transmission speeds, the energy consumption rates, and the acceptable proportions of the related heat development in the electronic circuits are just a few of the difficulties that 6G networks will face in the future, even though scientific advancements are experimenting with devices that can operate at higher frequencies. Due to their extensive coverage of the unexplored spectrum (unused frequency waves in the electromagnetic spectrum), studies predict that 6G networks would most likely function in frequencies between 100 GHz and 3 THz.

The term "wireless cognition," which alludes to wireless networks that might enable free movement of human thoughts over the air, is frequently used by the scientific community to describe 6G. AI applications and remote robots could exchange data at amazing speeds and with excellent coverage in the future thanks to 6G's electromagnetic frequencies. The sub-Terahertz bands would also contain the 6G frequencies. Therefore, based on these many bands, researchers estimate that it could transmit extremely fast calculations across a wide range of frequencies, allowing future mobile devices to have much more amazing capabilities, like human-machine interactions.

2 6G architecture

The architecture of 6G technology is expected to be extremely intelligent, sustainable, and cyber-resilient, with an emphasis on utilizing new spectrum technologies, AI, and advanced computing. A possible quantum communication backbone, improved edge computing, and a modular design are important features. In addition, the architecture will prioritize digital inclusion, security, and privacy with an eye toward cost reduction and ubiquitous connectivity.

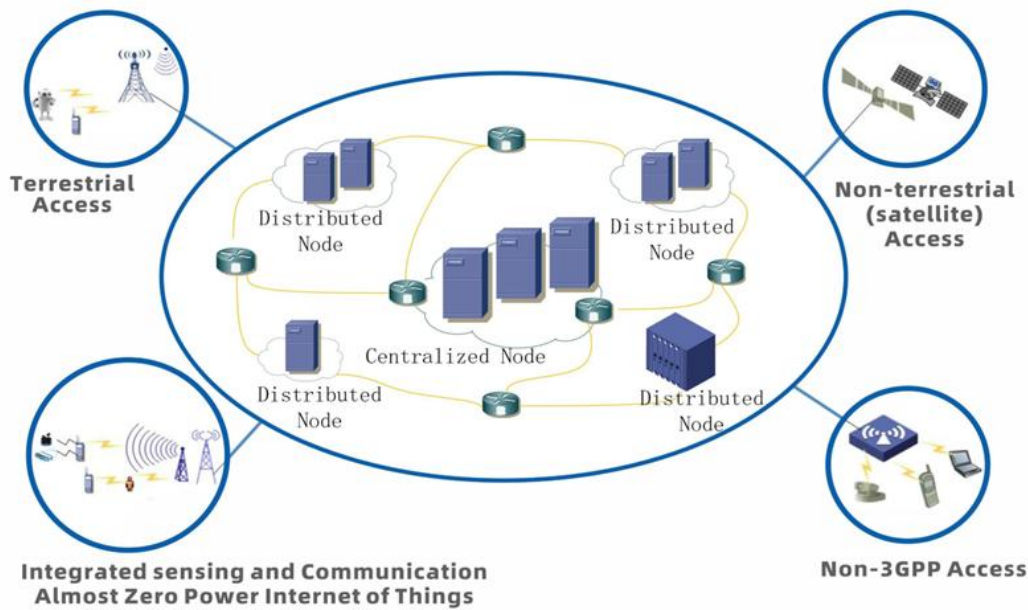


Figure 1 6G architecture

From the standpoint of the air interface, multiple protocol layers may be shared by various planes. Every plane has a different protocol layer configuration, though. Consequently, it is possible to reuse protocol layers across various planes. Each plane's unique requirements can be satisfied in the interim. According to CN, every plane comprises distinct network functions, each with specific duties as illustrated in Figure 1. 6G may introduce additional planes based on the control plane and user plane, as well as data planes, depending on the plane and function characteristics. The planes work together to support the essential native traits, such as native security, native intelligence, and native computing. This makes the services available to users. In addition to supporting basic information services like ISAC and converged computing services like integrated AI and communication (IAIAC), it also supports super communication services like 6G NTN and AZP-IoT.lt.

3 6G applications

It is anticipated that 6G applications will transform a number of industries through improvements in computing, sensing, and communication. Improved mobile broadband, fixed wireless access, integrated communication and sensing, and new opportunities for automation and artificial intelligence are a few examples. Additionally, a wide range of services will be made possible by 6G, including remote surgery, smart cities, autonomous cars, holographic communication, and immersive extended reality. A summary of the applications is shown in Figure 2.

4 Literature survey

The paper in [1] outlines the network architecture and future 6G wireless communication vision. This article discusses new technologies that can help the development of the 6G architecture ensure the quality of service (QoS), including artificial intelligence, terahertz communications, wireless optical technology, free-space optical network, blockchain, three-dimensional networking, quantum communications, unmanned aerial vehicles, cell-free communications, integration of wireless information and energy transfer, integrated sensing and communication, integrated access-backhaul networks, dynamic network slicing, holographic beamforming, backscatter communication, intelligent reflecting surface, proactive caching, and big data analytics. Additionally, potential technologies and anticipated applications with 6G communication requirements are presented. Authors also outline possible obstacles and lines of inquiry to reach this objective.

A groundbreaking study regarding the possible use of 6G to support such extremely demanding applications is presented in [2]. In order to accomplish this, we simulate a 6G system and carry out a case study investigating the use of drone-swarm-based surveillance concepts in a high-definition video monitoring application. Large volumes of video data must be sent over the network in this scenario. The obtained results demonstrate that 6G can handle these high demands on network traffic.

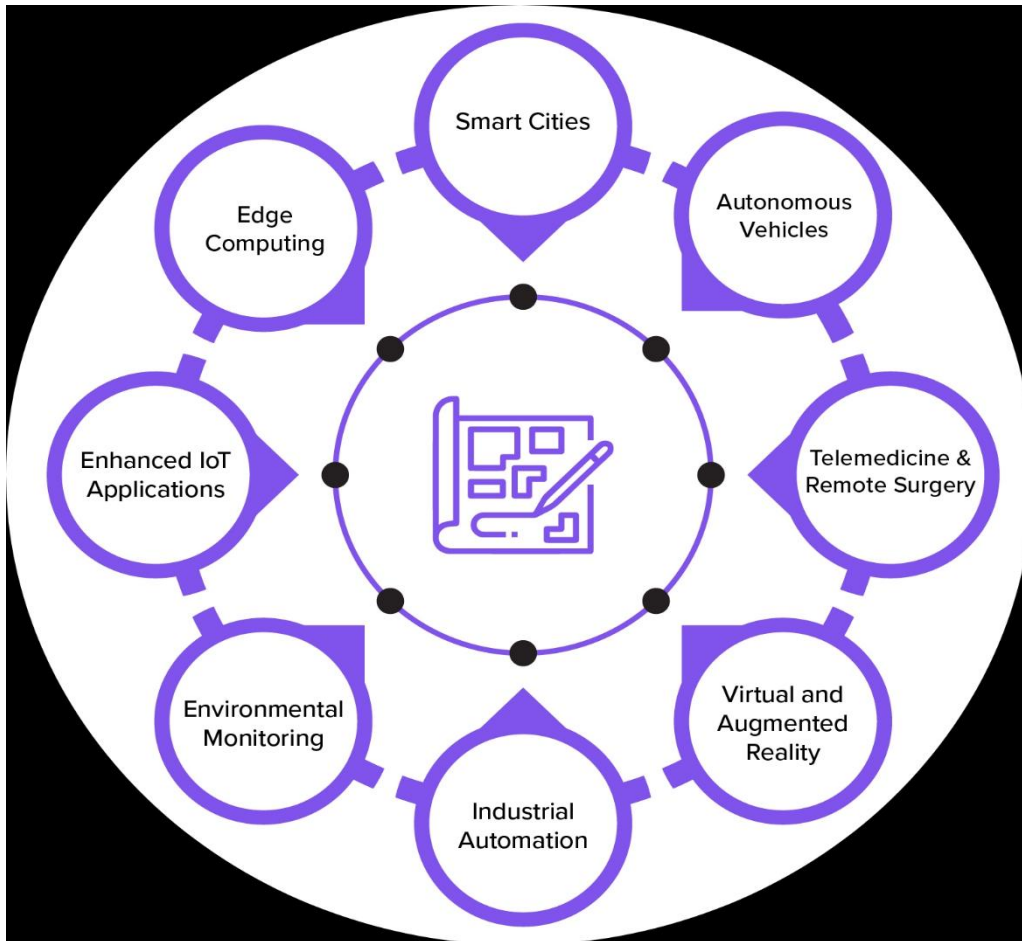


Figure 2 Block diagram of 6G applications

The key technological components required to deploy a 6G communication system are presented in [3]. The creation of an energy-efficient wireless network is the fundamental prerequisite. Intelligent Reflecting Surfaces (IRSs), which are straightforward and reasonably priced structures, are being considered as a replacement for massive MIMO in recent years. The benefits of combining IRSs with other technologies are discussed by the authors of this paper in order to satisfy the demands of next-generation wireless technologies. We go over recent studies on IRS design, IRS multi-cell application, IRS parameter optimization, and the impact of IRS in conjunction with deep learning.

First, the vision and requirements of 6G networks are discussed in [4]. The main enabling technologies that could be used by 6G networks are then discussed. We will pay close attention to index modulation, intelligent surfaces, visible light communications, and terahertz communication technologies. The presentation concludes with a number of issues facing upcoming 6G networks and possible future paths.

The purpose of the paper in [5] is to get a glimpse of the future of wireless communication and related technologies. 6G is anticipated to completely transform the digital world thanks to its higher transmission rate, enhanced spectrum efficiency, larger connection proportions, increased spectrum coherence, and significantly lower latency. The results of a thorough investigation into the development of 6G are presented in this paper. This comprehensive survey's primary focus is on 6G in relation to mobile communication and the major technologies that are anticipated to be deployed on networks enabled by 6G. This paper concludes by outlining current research projects being conducted by different research organizations.

A paper reviewing the state-of-the-art in 6G is found in [6]. With the help of cutting-edge technologies like SC, AI, and ML, authors hope to give readers a foundation in 6G research and an outline of how 6G will be utilized to develop applications. Additionally, the authors conceptualize and identify the role of 6G technology, along with its future challenges and vision. Along with a number of potential future applications for 6G, the authors have also covered the network and user side availability of 6G.

Investigating communication technologies and issues on 6G networks for the internet with the help of the Internet of Things (IOT) is the aim of the article in [7]. Based on a secondary data collection method, the researcher has established a procedure for gathering pertinent data and information about the subject matter. The researcher has used it to guide the

study in the right direction. Likewise, qualitative techniques were employed in the gathered materials to make the data more comprehensible. Additionally, this research will assist readers in comprehending the appropriate efficacy of strategies to alleviate the difficulties in the 6G network system. There are several benefits and challenges associated with implementing a sixth-generation network system, including creating an environmentally friendly, cost-effective network that is compatible with mobile devices and linked to artificial intelligence (AI) technology to increase performance. Issues with the next implementation are discussed in this paper.

In order for 6G networks to transition into green networks, research in [8] intends to concentrate on augmenting artificial intelligence in 6G networks.

A thorough review of previous research on the integration of blockchain and artificial intelligence with 6G wireless communications can be found in [9]. More precisely, authors begin with a synopsis of AI and blockchain. The authors then primarily examine the latest developments in the combination of blockchain and artificial intelligence, emphasizing the unavoidable trend of using both technologies in wireless communications. Additionally, the authors thoroughly examine how blockchain and AI can be integrated into wireless communication systems, encompassing secure services and intelligent Internet of Things (IoT) applications. In particular, some of the most talked-about core blockchain and AI-based services are presented, including content caching, spectrum management, computation allocation, security, and privacy. Moreover, authors also focus on some important IoT smart applications supported by blockchain and AI, covering smart healthcare, smart transportation, smart grid, and unmanned aerial vehicles (UAVs). The authors also go into great detail about 6G requirements, visions, and operating frequencies. The authors also examine the unresolved problems and research obstacles related to the integration of blockchain technology and artificial intelligence in 6G wireless communications. Finally, this paper attempts to give a thorough overview of blockchain and AI in 6G networks based on a large number of existing significant works. The survey's creators hope it will provide fresh insight into the study of this recently developed field and act as a guide for future research.

The paper in [10] first gives a thorough overview of the 6G vision, technical specifications, and application scenarios, covering the general consensus on 6G at the moment. The architecture of the 6G network and its main technologies are then critically evaluated. For the first time, advanced 6G verification platforms and testbeds are described in detail. Future research avenues and unresolved issues are also noted in order to further the ongoing international discussion. Lastly, the lessons learned about 6G networks thus far are reviewed.

The 6G WCN framework is presented in [11] along with an example of its main technologies. With the help of a communication scenario demonstration, the various 6G technologies are thoroughly explained, improving key performance indicators with significant variations. The explanation of 6G with the technologies that significantly affect the characteristics of a wireless communication network, including data rate, spectrum efficiency, energy efficiency, connection density, and reliability, is the main contribution of this paper. Each of these technologies has the potential to completely transform the next WCN.

The article in [12] functions as a thorough introduction to 6G by offering a broad overview, a current analysis of the key literature, and an educational tutorial-style presentation format. According to our vision, 6G will be built upon three core components: the Internet of Everything, wireless, and artificial intelligence. 6G can therefore eventually develop into the Intelligent Network of Everything and act as a foundation for mobile intelligence, the next significant development in mobile communication. Mobile intelligence has the potential to make anything intelligent, connected, and aware of its surroundings. This will completely change how systems, apps, and devices are made, how they work and communicate with one another and with people, and how they can be used to benefit individuals, society, and the entire world. The primary details of 6G, such as its essential components, disruptive applications, and important use cases, are covered after high-level visioning. Particular attention is paid to a wide range of prospective 6G technologies, each of which is presented in a tutorial fashion along with a discussion of the literature, future research directions, opportunities, challenges, history, and future. Lastly, we make some predictions about what will happen after 6G and provide the first high-level overview of 7G. Overall, the goal of this article is to give a comprehensive overview of 6G so that it can be used as a resource and source of inspiration for future research and development projects in industry, academia, and standardization organizations.

With an emphasis on resource management, self-healing, and network security, the paper in [13] suggests an AI-driven framework for 6G networks. It uses machine learning to improve fault recovery, lower latency, and make better decisions in real time. The efficacy of the framework is confirmed by simulations, which also provide scalable solutions for 6G deployment.

The article in [14] reveals how 6G is changing industries, bringing about economic growth, and addressing societal issues. Using contemporary technologies such as terahertz waves and massive MIMO systems, which 6G networks dominate, to achieve data rates, latency, and reliability, the latter provides progressive implementations across various domains. The new idea of human-machine interaction with the new 6G technology is nothing more than a hope for an inventive future. Its applications extend beyond reality to include remote surgery using real-time machines and automated smart factories, as well as communication of autonomous vehicles and immersive experiences. Secondly, a more inclusive society with less economic inequality will result from 6G, which ushers in a new era of growth. 6G networks

have the potential to accelerate justice and empower those who were previously marginalized by creating jobs, increasing wealth, and lowering greenhouse gas emissions. Although 6G has many potential risks, particularly in the form of privacy violations, cyberattacks, and network vulnerabilities, the technology itself may also be the cause of these issues. This is supported by the proactive risk management planning, robust security protocols, and the guarantee that 6G networks won't be violated.

The 6G concept is first explained in detail in the study in [15]. The operation of the proposed framework is verified at higher-order modulating plans to achieve higher spectrum efficiencies using performance indicators like error vector size, symbol constellations, and antenna array radiating beams. The performance findings strongly recommend using more data flows per user in order to achieve higher speeds that satisfy 6G wireless networks' requirements. They also recommend using a particular mMIMO antenna configuration based on the percentage of distinct data flows per user.

The survey article in [16] attempts to clarify the user-centric concept by thoroughly examining all of the different facets of 6G network architecture from a user-centric standpoint.

The study examines the promising features of 6G in [17], such as advanced sensing, accurate localization, and high-quality imaging. Machine learning (ML) and artificial intelligence (AI) will be extensively integrated into 6G technology, particularly in smart cities, where they will play a critical role in raising the standard of living for residents. 6G-enabled apps will support cutting-edge services that improve urban living experiences, tackle environmental issues, and offer more effective solutions across industries by integrating various components for monitoring, analysis, planning, and execution.

5 Conclusion

With much faster speeds, reduced latency, and increased capacity over 5G, 6G technology promises to revolutionize connectivity. Numerous new applications and use cases in a variety of industries, including manufacturing, entertainment, healthcare, and smart cities, will be made possible by this evolution. Although it is still in the early stages of development, 6G is anticipated to be commercially available by the early 2030s, with major improvements anticipated around 2028.

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