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Spatial Spillover Effects of Transportation Accessibility and Digitalization on Brain Drain: Evidence from North Sumatra

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Abstract. Brain drain, particularly the out-migration of university graduates, continues to present significant challenges for regional development in developing economies. This study investigates the extent to which transportation accessibility and digitalization influence graduates' decisions to migrate from North Sumatra, Indonesia, while incorporating spatial spillover effects across neighboring provinces. Using primary data collected through structured questionnaires, the analysis employs the Spatial Durbin Model (SDM) to capture both direct and indirect interregional effects. Transportation accessibility is measured through indicators such as the ease of reaching public transportation in the region of origin and the adequacy of transportation facilities at the destination. In parallel, digitalization is assessed through variables including internet availability in the region of origin and the role of digital platforms in facilitating job search activities. The findings indicate that limited accessibility to transportation and inadequate digital infrastructure in the origin region significantly increase the likelihood of graduate out-migration. Moreover, the use of digital platforms and professional networks functions as a strong catalyst, broadening employment opportunities beyond local boundaries. Importantly, spatial spillover effects are evident: improvements in transportation systems and digital penetration within North Sumatra Province exert influence on surrounding areas, either alleviating or intensifying migration pressures. These results highlight that graduate mobility is not solely shaped by local conditions but also by interregional interdependencies. The study contributes to migration and regional inequality literature while offering policy insights that emphasize integrated strategies to strengthen transportation and digital ecosystems, thereby retaining skilled graduates.

Keywords: Braindrain; Out-Migration; Spatial Durbin Model

INTRODUCTION

The phenomenon of brain drain, particularly the departure of university graduates from their home regions, is a crucial issue for regional development in developing countries. Investment in higher education yields an increase in the number of knowledgeable workers, but these benefits will diminish if suitable job opportunities, supporting infrastructure, and an innovation ecosystem are not evenly available at the regional level. When the most productive and innovative graduates leave their home region, the region's capacity to promote resource downstreaming and value-added industrial development will weaken an impact that ultimately hinders the industrialization process and local economic growth.

North Sumatra province shows that approximately 13.74% of the province's population is recorded as lifetime out-migrants, while in-migration is only 3.77% (BPS, 2020). The lifetime net migration is −10.93 (BPS, 2022). Additionally, 2015–2020 showed a 47.04% increase in out-migration of university graduates (BPS, 2015; BPS, 2020). This statistic indicates that the tendency for graduates to seek opportunities

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outside their home region is increasing. This train not only highlights demographic pressures but also signifies an imbalance between the availability/unavailability of value-added employment opportunities and the availability of infrastructure particularly transportation and digital access which are crucial determinants of highly educated groups' mobility. This condition will certainly impact the slowdown of the global sustainable development agenda. This is particularly true for Sustainable Development Goal (SDG) number 8, which prioritizes the creation of productive and inclusive jobs and sustainable economic growth. Additionally, this condition also impacts SDG 9, which highlights the role of infrastructure, industrialization, and innovation as pillars of economic development. In fact, according to Br Bancin et al. (2023) and Sabrina (2021), North Sumatra needs superior, creative, and innovative human resources to drive progress in the digital era (Industry 4.0 Revolution) in order to accelerate workforce readiness and support inclusive industrial transformation. Without interventions that strengthen transportation accessibility, digital connectivity, and the creation of value-added jobs at the district/city level, downstreaming and industrialization efforts in North Sumatra risk stagnation due to the loss of skilled human capital.

Initially, the brain drain phenomenon was a term that had existed for a long time, dating back to the 1960s and 1970s. Brain drain is the movement of highly educated labor between countries (Andrijevi & Bilas, 2010; Permatasari et al., 2021). However, with the development of regional economic studies and increased labor mobility, the concept of brain drain is no longer limited to the international context. This term is now also used to describe the movement of highly educated graduates between regions or provinces within a single country. (Blanco-Moreno, 2024; Krisnandita, 2023; Nguyen, 2022). Furthermore, other studies have examined the factors influencing brain drain at the regional level in general (Kasnauskiene & Palubinskaite, 2020; Vega-Muñoz et al., 2024, 2025). In Indonesia, the phenomenon of brain drain has also been discussed (Muslihatinningsih et al., 2022; Pardede et al., 2020; Permatasari et al., 2021; Saefuloh, 2012; Simanjuntak & Pasaribu, 2023; Yunitasari et al., 2021). However, studies on brain drain in North Sumatra Province have been conducted extensively, focusing on fundamental issues such as education, health, and poverty (Hasibuan et al., 2024; Rahmadani et al., 2024; Sihombing, 2022). Nevertheless, in the current digital age and modern mobility, new factors such as transportation accessibility and the level of digitalization play an increasingly significant role in influencing the migration decisions of university graduates. Adequate transportation infrastructure can improve interregional connectivity, thereby expanding job location options and accelerating the flow of educated labor mobility. Meanwhile, digitalization through internet penetration, online professional platforms, and remote working systems opens up new opportunities for graduates to work across regions without strict geographical boundaries. Although brain drain studies in North Sumatra have made significant contributions to understanding the socio-economic dimensions, the integration of transportation and digitalization variables remains a relevant area of research to deepen our understanding of graduate migration dynamics in this region. Therefore, the purpose of this research is to analyze the influence of transportation accessibility and digital access on the migration decisions of university graduates. Additionally, this study also identifies the spatial spillover effects of transportation and digital infrastructure.

The contribution of this research is both theoretical and policy-oriented. Theoretically, this study enriches the human capital and migration literature by

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incorporating physical and digital infrastructure variables as drivers of graduate migration decisions and by highlighting the role of inter-regional spatial interactions. From a policy perspective, the research findings provide empirical evidence that policymakers can use to design integrative strategies combining improved transportation access, digital infrastructure expansion, and the creation of value-added jobs to stem talent outflow and accelerate the process of inclusive downstreaming and industrialization.

LITERATURE REVIEW

The relationship between human capital and the motivation to migrate among educated graduates can be explained through the economic migration theory framework, which views migration as a form of individual investment in human capital. From this perspective, individuals with higher levels of education and skills (greater human capital) evaluate migration not merely as a geographical move, but as an economically rational choice to increase the return on their knowledge and abilities. Human capital theory (Schultz, 1961) states that investment in education and training increases individual skills, which in turn boosts productivity and income. Sjaastad's (1962) classical theory treats migration as an investment in "human capital": potential migrants weigh the direct costs (moving expenses, adaptation) and opportunity costs (time, risk) against the expectation of higher income at the destination. For educated graduates, the wage difference between place of origin and destination is often accompanied by differences in career opportunities such as access to high-tech job sectors, research opportunities, or qualification recognition which increases the relative incentive to migrate. Additionally, the accumulation of human capital is dynamic: work experience at the destination location can enhance practical skills and professional networks, thereby influencing long-term decisions such as settling down. Korpi & Clark (2017) emphasize that internal migration is often influenced by differences in income potential and employment opportunities, particularly for individuals with higher levels of education.

Technological developments also shape people's decisions to relocate: as innovations from automation to digital services shift labor market needs, graduates and skilled workers tend to seek locations that offer higher rewards and skills development opportunities; on the other hand, their departure can also trigger the spread of technology and knowledge back to their home regions through networks, remittances, or the return of migrants (Andersson et al., 2022). The presence of technology is also evident in the increased innovation activity and capital intensity in both the agricultural and industrial sectors in regions experiencing emigration, as the departure of labor spurs the adoption of labor-saving technologies (Acemoglu & Restrepo, 2019; Andersson et al., 2022). Differences in technology across regions also impact disparities in technological adaptation between regions, for example, between areas with traditional economic structures and innovation hubs. These considerations will motivate educated workers to migrate to more technologically advanced locations, while improvements in transportation infrastructure reduce physical barriers, making this mobility easier to achieve (Heuermann & Schmieder, 2019; Lu et al., 2022). Finally, while wage differences often trigger the "brain drain" phenomenon, deep gaps in the innovation ecosystem can also trigger it. The direction of this movement is not always permanent, meaning the flow of knowledge can transform it into development benefits (Docquier & Rapoport,

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2012). Thus, the relationship between technology and migration is two-way: technological advancements in destination regions can attract highly educated migrants, while migration itself can accelerate technological development in origin regions through knowledge transfer and increased capital intensity. Understanding these dynamics is crucial for designing inclusive human development and innovation policies, ensuring that labor mobility not only leads to the movement of human resources but also to the exchange of knowledge that drives sustainable development.

Other research related to digitalization has transformed the labor market landscape by creating new opportunities through online platforms. (Zaborovskaia et al., 2020) analyzed the influence of digitalization factors on the formation and development of human capital in 82 regions of the Russian Federation (period 2014–2018). Human capital formation and testing its relationship with 34 digitalization indicators, namely digital infrastructure, internet usage rates, and digital public services. Regression results show a positive relationship between digital development and human capital/quality at the regional level. This finding indicates that digitalization expands access to information, facilitates distance learning/education, and opens up online job opportunities that support worker skills and capacity building. Furthermore, another opinion states that interregional migration decisions have spatial spillover effects. (Blanco-Moreno, 2024) shows that the migration decisions of college graduates are not only influenced by conditions in their origin and destination areas, but also by interregional dynamics. Improvements in transportation infrastructure and digitalization in one region can attract migrants from surrounding areas, creating complex migration patterns.

Therefore, access to transportation and digitalization are interconnected in influencing the migration decisions of college graduates. Good transportation access allows individuals to seek job opportunities in other regions at a lower cost, while digitalization provides a platform for searching for information and applying for jobs online. The combination of both expands the range of economic opportunities for college graduates,

In the context of North Sumatra Province, the migration dynamics of university graduates reflect the theoretical foundations previously discussed. The uneven distribution of transportation and digital infrastructure across regions in Indonesia, particularly between urban and peripheral island areas of North Sumatra, creates disparities in economic and professional opportunities that drive the outmigration of highly educated individuals. Improved transportation accessibility in destination areas reduces geographical barriers and enhances spatial mobility, while more advanced digital infrastructure facilitates job searches and expands professional connectivity across regions. These findings are consistent with Heuermann and Schmieder (2019) and Lu et al. (2022), who emphasize that both transportation infrastructure and technological access play crucial roles in lowering mobility frictions and accelerating the redistribution of skilled labor.

Furthermore, the digitalization of destination regions characterized by better internet quality, online job platforms, and digital work ecosystems strengthens migration incentives among university graduates. This highlights that non-monetary factors such as innovative environments, lifelong learning opportunities, and professional networking have become critical determinants of migration decisions, as suggested by Andersson et al. (2022) and Acemoglu and Restrepo (2019). Within the framework of

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sustainable development, this brain drain phenomenon poses challenges to achieving Sustainable Development Goal (SDG) 8 on inclusive and productive employment, and SDG 9 on resilient infrastructure, industrialization, and innovation. Accordingly, regional governments in North Sumatra must develop integrated strategies that enhance transportation accessibility and digital ecosystems to retain local talent while promoting the sustainable circulation of knowledge.

Therefore, this study addresses a significant research gap by examining the influence of transportation accessibility and digitalization on graduate outmigration in North Sumatra using the Spatial Durbin Model (SDM) approach. This model enables the analysis of both direct and spatial spillover effects, capturing the extent to which improvements in infrastructure and digital connectivity in one region affect migration behavior in neighboring areas. By doing so, the study contributes conceptually to the expansion of human capital theory in the context of internal migration in developing economies and offers evidence-based policy insights to promote balanced regional development and strengthen human capital resilience in North Sumatra.

Building on the theoretical framework of human capital and spatial migration dynamics, this study proposes that individual migration decisions among university graduates are shaped by the combined influence of transportation accessibility, digitalization, and spatial interdependence among regions. The *Spatial Durbin Model (SDM)* enables the analysis of both direct and spillover effects, revealing how improvements in transportation and digitalization in one province may indirectly influence migration tendencies in adjacent provinces. Based on these theoretical and empirical insights, we proposed the hypotheses that transportation accessibility has a significant positive effect on the outmigration of university graduates, indicating that greater access to transportation networks reduces mobility barriers and facilitates interprovincial movement. Digitalization exerts a significant positive influence on graduate outmigration, as better digital infrastructure and online platforms expand job search opportunities and professional networks beyond regional boundaries. There exists a spatial spillover effect of transportation accessibility and digitalization on graduate outmigration, implying that improvements in one region may indirectly affect migration patterns in neighboring regions through spatial interconnections. These hypotheses collectively reflect the interaction between human capital mobility, infrastructure availability, and spatial dependence, providing a multidimensional understanding of *brain drain* phenomena within the context of regional development in North Sumatra.

METHODS

The study focuses on North Sumatra, a province in Indonesia characterized by uneven infrastructure development and significant graduate mobility. Data are drawn from a combination of census-based records, regional statistics, and primary survey indicators related to graduate migration. This study uses a quantitative approach with a cross-sectional design to analyze the direct and indirect influence of transportation accessibility and digitalization on the migration of university graduates in North Sumatra Province. To capture the spatial effects between regions, an appropriate spatial econometric model is used.

This research uses primary data obtained directly through the distribution of questionnaires to 351 respondents who are university graduates in North Sumatra

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Province. This is done to obtain empirical information that is contextual and relevant to the phenomenon of educated labor migration, specifically to explore the motivations, perceptions, and factors influencing the decision to migrate to other regions. The data collection technique using questionnaires was chosen because it is efficient in reaching respondents with heterogeneous characteristics and allows for structured measurement of variables based on previously designed indicators (Creswell & Creswell, 2018). The questionnaire in this study was designed using a structured survey approach with a combination of closed and open-ended questions. This survey-based approach has been widely used in similar research to analyze the determinants of labor migration and brain drain in various geographical contexts (Adjei-Mensah, 2023; Docquier & Rapoport, 2012). The research variables consist of: Dependent Variable: obtained from the migration decisions of university graduates; Independent Variables: Transportation Accessibility, which includes the ease of accessing public transportation in the area of origin (ATR1) and the availability of public transportation in the destination area (ATR2); and Digital Accessibility, which includes: Internet quality and speed in the area of origin. ATD1 Information technology infrastructure in the destination area (ATD2) The role of digital platforms or professional networks in supporting job searching (ATD3).

The analytical technique used in this study focuses on identifying spatial effects to understand the interregional linkages in the phenomenon of college graduate migration. This approach is based on the assumption that migration decisions in a region are not independent, but are influenced by the socio-economic and infrastructure conditions in surrounding areas. Methodologically, this research uses spatial econometric models, specifically the Spatial Autoregressive Model (SAR) and the Spatial Durbin Model (SDM). The SAR model is used to identify the extent to which migration decisions in one region are influenced by migration decisions in other regions through the neighbor effect (spatial lag effect). Meanwhile, the SDM model was chosen because it can accommodate both the direct and indirect effects (spillover effect) of independent variables on surrounding regions (Elhorst, 2014). SDM allows for the identification of direct (endogenous) and spillover (external) effects of independent variables on the dependent variable, as well as interactions between neighboring regions. This model has proven effective in analyzing migration phenomena and other spatial distributions (Myovella et al., 2021). Before estimating the model, this study first conducted a series of spatial diagnostic tests to confirm the presence of significant spatial effects, including the Moran's I test, Multicollinearity test, and Goodness of Fit/R-Squared Spatial. This study considered the Akaike Information Criterion (AIC) and Schwarz Criterion (BIC) values (LeSage & Pace, 2009).

RESULTS AND DISCUSSION

Descriptive analysis in this study aims to provide a general overview of respondents' perceptions regarding variables representing transportation accessibility and the level of digitalization in the context of college graduates' decisions to migrate out. The measurement scale used ranges from 1 (strongly disagree) to 4 (strongly agree), with the provinces that are the destination areas for graduate migration being Aceh Province, Riau, West Sumatra, South Sumatra, DKI Jakarta, Riau Islands, West Java, Central Java, Yogyakarta, East Java, West Kalimantan, and South Sulawesi. The analysis results show that the variable of ease of access to public transportation in the area of

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origin has the highest average value, which is 3.63. These indicate that most respondents consider public transportation access in their area of origin to be relatively easy. Meanwhile, the availability of public transportation in the destination area has an average value of 3.08, reflecting a fairly good perception of the availability of transportation facilities in the migration destination area. Regarding the aspect of digitalization, the quality and speed of the internet in the area of origin received an average score of 2.44, indicating that the quality of digital infrastructure in the area of origin is still considered limited. Conversely, the variable of information technology infrastructure in the area of destination has an average score of 3.43, confirming that migration destination areas generally have better digital infrastructure quality compared to the area of origin. Additionally, the variable (the role of digital platforms or professional networks in supporting job searching) obtained an average value of 3.323, indicating that the digitalization factor plays an important role in expanding access to information and job opportunities for university graduates. Overall, these descriptive results show that disparities in transportation access and digitalization between regions have the potential to be both push and pull factors in the phenomenon of out-migration of highly educated workers in North Sumatra. In summary, the statistical data used in this study are as follows:

Table 1. Data Summary

Variabel	Mean	Min	Max
1. Accessibility of public transportation in the region of origin (ATR1)	3.632	3	4
2. Availability of public transportation in the destination region (ATR2)	3.088	2.5	4
3. Quality and speed of internet connectivity in the region of origin (ATD1)	2.443	1	3
4. Information and communication technology (ICT) infrastructure in the destination region (ATD2)	3.425	3	4
5. The role of digital platforms or professional networks in facilitating job search activities (ATD3	3.323	3	4

Source: process data

Before proceeding with the spatial model analysis, validity and reliability testing was conducted on the instruments used namely, five indicators measuring transportation accessibility and digitalization (ATR1, ATR2, ATD1, ATD2, ATD3). From the reliability test, a reliability coefficient of 0.7396 was obtained, indicating that the instrument has good internal consistency and is above the generally accepted minimum threshold ($\geq$ 0.70). This value is also supported by an average inter-item covariance of 0.1249, which indicates that the items have a sufficiently adequate positive correlation without being overly redundant. (F. Hair Jr et al., 2019) state that a Cronbach's alpha value $\geq$ 0.70 is generally accepted as the minimum reliability threshold in research. Furthermore, Cronbach's alpha explains the measure of internal consistency, although it is not an absolute tool for validity, making high reliability a prerequisite for an instrument to be usable in advanced statistical analysis (Tavakol & Dennick, 2011).

Regarding validity, the indicators used are able to reflect the theoretical constructs, namely perceptions of transportation accessibility and digitalization. The results of the correlation analysis between variables show varying relationships between the

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dimensions of transportation accessibility and digitalization in the context of out-migration of university graduates in North Sumatra Province. The strong correlation value between ATR1 (ease of access to public transportation in the origin area) and ATR2 (availability of public transportation in the destination area) of 0.6027 indicates that the easier the access to transportation in the origin area, the higher the perception of the availability of transportation facilities in the destination area. A fairly strong relationship is also seen between ATR2 and ATD5 (information technology infrastructure in the destination area) with a correlation value of 0.6782, which shows a positive link between transportation progress and the readiness of digital infrastructure in the migration destination area.

Meanwhile, ATD1 (internet quality and speed in the region of origin) shows a negative correlation with most other variables, such as ATR2 (-0.1253) and ATD5 (-0.2760), which can be interpreted as meaning that the lower the digital quality in the region of origin, the greater the likelihood that individuals will be interested in moving to areas with better digital facilities. Additionally, the positive correlation between ATD6 (the role of digital platforms or professional networks in job searching) with ATR1 (0.5430) and ATR2 (0.6117) suggests that the ease of physical mobility tends to align with the increasing use of digital technology in job searching. In general, this correlation pattern describes a strong link between transportation and digitalization as two main dimensions that mutually reinforce each other in influencing the out-migration decisions of university graduates. Thus, the instrument can be said to be sufficiently valid and reliable for use in further analysis. Table 2 shows the results of the multicollinearity test, indicating that the average Variance Inflation Factor (mean VIF) value is 1.86. This value is far below the common threshold often used in econometric analysis, which is 10, as recommended by (Gujarati, 2003; Wooldridge, 2010). Thus, it can be concluded that there are no serious multicollinearity issues among the independent variables in this research model. The results of the VIF value calculation.

Table 2. Multicollinerity Test

Variable	VIF	1/V*IF*
1. Accessibility of public transportation in the region of origin (ATR1)	2.55	0.391
2. Availability of public transportation in the destination region (ATR2)	2.11	0.474
3. Quality and speed of internet connectivity in the region of origin (ATD1)	1.80	0.556
4. Information and communication technology (ICT) infrastructure in the destination region (ATD2)	1.74	0.575
5. The role of digital platforms or professional networks in facilitating job search activities (ATD3	1.10	0.910
Mean VIF	1.86	

Source: data process

The results of the Moran's I test data processing show that chi2 is 1.74 with Prob > chi2 = 0.1875. The results of Moran's test in this study did not show significant spatial autocorrelation. Methodological and empirical literature indicates that the global Moran's I non-significance does not rule out the possibility that a SAR model or, more generally, an SDM, is still appropriate. Ren et al. (2024) mention that Moran's I test results indicate the presence of spatial autocorrelation in the data, but do not identify

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the appropriate type of spatial model (lag or error). The non-significant global Moran's I test does not automatically rule out the possibility of spatial effects. This is because the global Moran's I test only captures general patterns, while local patterns or theoretical constructs can drive the selection of a spatial lag or Durbin model. (Dong et al., 2024) used the Wald test to select the Spatial Durbin Model (SDM).

Table 3. Wald Test

Variable	Wald	Sign.
1. Accessibility of public transportation in the region of origin (ATR1)	38.97	0.0000
2. Availability of public transportation in the destination region (ATR2)	27.79	0.0000
3. Quality and speed of internet connectivity in the region of origin (ATD1)	6.47	0.0393
4. Information and communication technology (ICT) infrastructure in the destination region (ATD2)	49.76	0.0000
5. The role of digital platforms or professional networks in facilitating job search activities (ATD3	41.14	0.0000

In an effort to select the best spatial model to explain the phenomenon of high-skilled graduate migration, this study employs the information criteria comparison approach as its primary guide. The non-spatial OLS model shows AIC = 13.47 and BIC = 16.86, while the SAR model yields AIC = 16.98 and BIC = 21.50. Conversely, the Spatial Durbin Model (SDM) records AIC = 3.061 and BIC = 10.41, which are the lowest values among the tested models. Based on the principle that a better model is one with the smallest AIC and BIC (more efficient in balancing goodness-of-fit and parameter complexity) (Agiakloglou & Tsimpanos, 2023), these results indicate that SDM empirically outperforms both OLS and SAR as the preferred specification. (Table 4). This approach is consistent with simulation results and methodological studies that validate the effectiveness of AIC and BIC in selecting spatial models, including SDM, within the context of various non-nested spatial models (Agiakloglou & Tsimpanos, 2023).

Table 4. Selection Model Spatial Braindrain Sumatera Utara

Variable	OLS	SAR	SDM
Accessibility of public transportation in the region of origin (ATR1)	-0.00612 (0.215)	0.0131 (0.155)	-2.017*** (0,327)
Availability of public transportation in the destination region (ATR2)	0.00228 (0.278)	-0.0207 (0.200)	-1.090*** (0.219)
Quality and speed of internet connectivity in the region of origin (ATD1)	-0.000379 (0.153	-0.00290 (0.109)	-0.392* (0.173)
Information and communication technology (ICT) infrastructure in the destination region (ATD2)	0.0661 (0.282)	0.0790 (0.201)	3.342*** (0.497)
The role of digital platforms or professional networks in facilitating job search activities (ATD3	0.0335 (0.267)	0.0168 (0.191)	0.991** (0.324)
Constanta	0.581 (0.929)	1.041 (0.936	-66.29*** (12.61)

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Variable	OLS	SAR	SDM
Wdis		-0.497	-0.580
Braindrain		(0.715)	(0.531)
Accessibility of public transportation in the region of origin (ATR1)			0.698 (0.852)
Availability of public transportation in the destination region (ATR2)			4.273** (1.315)
Quality and speed of internet connectivity in the region of origin (ATD1)			0.864 (0.747)
Information and communication technology (ICT) infrastructure in the destination region (ATD2)			29.92*** (4.246)
The role of digital platforms or professional networks in facilitating job search activities (ATD3			-15.08*** (2.366)
/var(e.)Braindrain		0.0615* (0.0245)	0.00968* (0.00384)
BIC	16.86	21.50	10.41
AIC	13.47	16.98	3.061

Note: *p<0.05, ** p<0.01, *** p<0.001

Based on Table 4, there are substantial differences among the three OLS, SAR, and SDM models both in terms of statistical significance and the econometric meaning of the coefficients. In the OLS model, the brain drain coefficient is negative, and all measured variables are statistically insignificant. This indicates that the non-spatial approach fails to capture cross-regional linkages that may influence graduate migration patterns. These results highlight the limitations of OLS when the assumption of independence between spatial units is violated (Anselin, 1988). Next, in the SAR model, which incorporates the spatial lag of the dependent variable to capture neighborhood effects, only moderately changes the coefficient value (−0.580; s.e. 0.531) and does not result in significant shifts in the main variables, indicating that simple spatial dependence effects on the dependent variable alone are insufficient to explain the observed patterns (LeSage & Pace, 2009). However, the HR model shows much more meaningful information. Several variables related to the characteristics of the destination area became significant and had high coefficients. This condition is evident in the availability of public transportation in the destination region (ATR2), which shows a positive and significant coefficient, while ICT infrastructure in the destination region (ATD2) has a very strong and significant influence with p <0.001. This finding confirms that destination region attributes, particularly transportation availability and ICT capacity, can drive inter-provincial migration flows, and that these effects are easily overlooked when more complete spatial models are not used (Elhorst, 2014). Interestingly, the role of digital platforms/professional networks (ATD3) emerged with a negative and significant coefficient (−15.08, p<0.0001) in the spatial specification. This result indicates complex mechanisms (e.g., substitution between online job search and physical relocation, or saturation effects in destination centers) that require further examination through the decomposition of direct and indirect/spillover effects in human resources (LeSage & Pace, 2009).

Implicatively, the differences between the three models confirm two methodological and policy recommendations. First, the analysis of interprovincial

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migration determinants should use a model that accommodates spatial spillover (such as SDM) to identify both the direct influence of the origin region and the cross-regional effects of destination characteristics. Second, the finding that transportation infrastructure and digital capabilities are strongly correlated with migration flows is consistent with previous empirical evidence regarding the role of physical and digital infrastructure in facilitating labor mobility (e.g., the effect of HSR on worker mobility; Heuermann & Schmieder, 2019) as well as the relationship between digitalization and regional human capital formation (Zaborovskaia et al., 2020). Therefore, regional policies aimed at balancing talent flows need to consider the spatial dimension and the interaction between physical access (transport) and digital access (ICT/platforms) so that interventions can manage not only local retention but also spillover effects to neighboring regions (Anselin, 2021).

The human capital model in this study successfully demonstrated a significant spatial spillover effect, particularly on the variables of transportation availability in the destination area (ATR2) and information technology infrastructure in the destination area (ATD2), both of which had a positive and significant impact on the migration flow of university graduates. This finding confirms that brain drain is not only influenced by internal factors in the region of origin, but also by the structural attractiveness of the destination region, particularly in terms of transportation connectivity and digital infrastructure readiness (Elhorst, 2014; LeSage & Pace, 2009). Another finding is that the role of digital platforms or professional networks (ATD3), which has a negative coefficient in the human resource model, indicates that increased access to online professional networks is not always directly proportional to the physical mobility of the workforce. This may reflect the phenomenon of substitution between digital mobility and geographical mobility (Miguélez & Moreno, 2014), where individuals with higher digital access are more likely to take advantage of remote work opportunities without having to physically migrate.

Furthermore, this study also indicates two significant main contributions, both methodologically and theoretically. From a methodological perspective, this research strengthens the relevance of using spatial econometrics in analyzing the brain drain phenomenon and the mobility of educated labor across regions. This approach allows researchers to identify the presence of spatial dependence and spillover effects between regions using the Spatial Durbin Model (SDM). The human resource modeling in this study is able to break down the direct effects of internal variables within a region on migration decisions, as well as the indirect effects stemming from the characteristics of neighboring regions.

CONCLUSION

A theoretical contribution perspective, this research encourages the expansion of the conceptual framework toward the development of digital-driven migration theory, which emphasizes the role of digitalization and information technology infrastructure as new determinants in the mobility of educated labor in the digital economy era. This research indicates that digital connectivity, the quality of the internet network, and the presence of online professional platforms can be determining factors in migration decisions, both directly and through interaction with other spatial variables.

The integration of classical migration theory based on the push-pull model with the concept of digital accessibility provides a new direction in understanding contemporary migration patterns, which are increasingly influenced by technological transformation and global connectivity (Docquier & Rapoport, 2012). A policy perspective, the results of this study confirm the importance of regional development planning based on spatial bioeconomy and digital connectivity. Local and central governments need to improve the quality and accessibility of public transportation, both in the origin and destination areas, to balance inter-regional attractiveness and reduce the gap in the migration of educated workers. Next, another policy that can be implemented is to strengthen information and communication technology (ICT) infrastructure in underdeveloped areas so that access to digital-based job opportunities can be expanded, preventing all human resource potential from being concentrated in large cities. Spatial-based policies that integrate transportation development, digitalization, and human resource capacity are expected to strengthen regional competitiveness and reduce the rate of brain drain (OECD, 2022; Heuermann & Schmieder, 2019).

Although this study makes significant contributions both methodologically and theoretically to the study of brain drain and the mobility of educated labor, there are several weaknesses that need to be acknowledged as limitations of this research. First, the data used is cross-sectional, so it cannot yet capture temporal dynamics and changes in migration behavior over a specific period. Second, the measurement of variables such as internet quality or the role of digital platforms still relies on quantitative indicators that may not fully reflect qualitative aspects, such as connection stability or digital engagement. Third, the HR model used focuses on linear relationships, while modern migration phenomena are often non-linear or have threshold effects (Elhorst, 2014). Based on the findings and limitations identified, this study opens opportunities for further research to deepen and broaden the analysis of the brain drain phenomenon and the mobility of educated labor, namely by using spatial panel data to analyze the spatial dynamics of brain drain over time and test the stability of relationships between variables, incorporating social and institutional variables such as the quality of local governance, educational policy incentives, and private sector involvement in creating jobs for graduates, and conducting micro-level analysis based on individuals or households, for example, using IFLS data or the 2020 Population Census Long Form, to understand the determinants of migration decisions at the individual level. This approach is expected to enrich the theoretical and empirical understanding of how digital transformation, spatial infrastructure, and socio-economic factors interact to shape brain drain patterns in Indonesia.

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