 p-ISSN 2827-8585
e-ISSN 2827-8062

International Journal of Multidisciplinary Research and Literature
IJOMRAL
Vol. 5, No. 5, September 2026 pp. 886-895
Journal Page is available at http://ijomral.esc-id.org/index.php/home

MATHEMATICAL DESIGN MODEL BASED ON SMART AIRPORT CONNECTIVITY WITH AN INTEGRATIVE APPROACH IN THE TOD AREA OF SOEKARNO-HATTA AIRPORT

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Abstract

This study aims to analyze the priority design criteria for Terminal 4 of Soekarno-Hatta Airport based on Smart Airport Connectivity within the context of a Transit-Oriented Development (TOD) area, and to formulate a conceptual mathematical model for assessing the sensitivity of terminal design performance. The main research problem originates from the inefficiency of the existing terminal circulation, which tends to be linear, the weak integration of intermodal transport, and the potential conflict between passenger and baggage movement flows. This study applies a descriptive quantitative approach through a digital questionnaire distributed to 120 respondents, resulting in 100 valid responses for analysis. The analysis includes validity testing, reliability testing, descriptive statistics, and the synthesis of a third-order polynomial mathematical model, expressed as $y = ax^3 + bx^2 + cx + (d+e)$. The results show that comfort obtained the highest score at 2.27, followed by smart airport digital at 2.23, good connectivity at 1.99, safety at 1.97, and passenger-baggage integration at 1.59. In the simulation scenario, safety and comfort constants were assigned the maximum operational value of 3. The model simulation at peak load, $x = 11$, produced a design quality index of 3,232.41. These findings indicate that the digital system is the most sensitive factor in maintaining terminal performance under high-load conditions, while TOD integration acts as a spatial density buffer. The study recommends implementing a radial configuration, smart wayfinding, biometric gates, self-baggage drop, smart queue systems, a compact intermodal hub, and vertical separation of passenger and baggage circulation to create an efficient, safe, comfortable, navigable, and human-centered airport terminal.

Keywords: Smart Airport Connectivity, Transit-Oriented Development, Airport Terminal, Mathematical Model, Phygital Design

INTRODUCTION

Soekarno-Hatta International Airport is one of Indonesia's main air transportation nodes and accommodates large-scale movements of passengers, goods, and supporting transport modes. The increasing demand for air travel requires airport terminals not only to provide waiting areas and departure facilities, but also to form an efficient connectivity system from the landside to the airside. In this context, the planned development of Terminal 4 should be understood as an opportunity to improve the circulation pattern of the existing terminals, which tends to be linear and often creates long transfer distances for users.

The main issue in modern airport terminals is no longer limited to the fulfillment of minimum spatial standards. However, it concerns how physical space, digital systems, and public transportation networks can operate as a single ecosystem. Edwards (2005) emphasizes that modern terminals must balance transportation functions, public-space comfort, and seamless connectivity. Meanwhile, Horonjeff et al. (2010) explain that terminal configurations, whether linear, pier, or satellite, significantly affect the efficiency of passenger and aircraft movement.

The existing terminal conditions in the Soekarno-Hatta Airport area indicate the need for a more integrative design approach. Passenger movement from land transportation modes to check-in areas, security screening, immigration, waiting lounges, and boarding gates requires a clear orientation system. At the same time, the movement of goods and baggage requires a fast, secure flow that does not interfere with passenger comfort. If these two flows are not properly separated and managed, the potential for bottlenecks will increase during peak hours.

The concept of Smart Airport Connectivity is relevant because it connects physical infrastructure with real-time data-based information systems. Arthur D. Little and Amadeus (2019) explain that airport digital transformation can shift operations from merely fulfilling performance requirements toward strategic opportunities for improving the user experience. The integration of technologies such as the Internet of Things (IoT), biometric gates, smart signage, self-service check-in, self-baggage drop, and indoor navigation applications can accelerate processes, reduce queues, and help passengers make more accurate decisions.

In addition to digital systems, the Transit-Oriented Development (TOD) approach is an important basis for Terminal 4 development. ITDP (2017) emphasizes that TOD requires dense, connected, walkable areas integrated with public transportation. In the airport context, this principle can be translated into a compact relationship among the terminal, airport rail station, bus system, feeder transportation, drop-off areas, and parking facilities.

Based on this background, this study aims to analyze the priority design criteria for Terminal 4 based on Smart Airport Connectivity from the perspective of users, to construct a conceptual mathematical model for reading design performance sensitivity, and to formulate architectural recommendations that support the integration of passengers, goods, and transportation modes within the TOD area of Soekarno-Hatta Airport.

LITERATURE REVIEW

Terminal Configuration and Circulation Efficiency

Terminal configuration is a fundamental element that determines the relationship among landside areas, terminal processing, and airside operations. According to Horonjeff et al. (2010), a linear configuration can simplify spatial legibility, but in a large-scale terminal it may extend walking distances. Pier and satellite configurations can increase apron capacity, but require effective connector systems. Therefore, the design of Terminal 4 needs to combine the efficiency of physical configuration with navigational technology support so that passenger movement remains intuitively legible.

In Indonesia, passenger terminal facilities are regulated through aviation standards and regulations, including Minister of Transportation Regulation No. PM 36 of 2021 concerning Airport

Facility Standardization and Ministerial Decree No. KM 48 of 2008 concerning the Master Plan of Soekarno-Hatta Airport. These regulations are important as a basis for safety and capacity, but future terminal design must also consider users' perceptions of comfort, speed, and ease of orientation.

Smart Airport Connectivity

A smart airport is a concept of airport development that integrates digital technology, information systems, real-time data, and automated service processes. In the architectural context of a terminal, technology does not stand as an additional device, but becomes part of the spatial strategy. Digital systems can help passengers directly identify their location, estimate travel time to gates, monitor queue status, check baggage status, obtain flight information, and access alternative transport modes.

Smart connectivity can be understood as a bridge between physical space and digital experience. When passengers receive accurate information, spatial uncertainty can be reduced. Therefore, a smart airport not only improves operational efficiency but also reduces the psychological pressure that users often experience due to queues, delayed information, and unclear directions.

Transit-Oriented Development in Airport Areas

TOD in airport areas positions the terminal as a meeting point between air transportation and ground transportation. This integration requires short transfer distances, comfortable pedestrian paths, integrated information systems, and direct connections to public transportation modes (ITDP, 2017). In the development of Terminal 4, TOD should not merely be understood as the provision of a station or a bus stop, but as an area structure that unifies passenger movement from arrival in the airport district to the boarding gate.

Good TOD integration can function as a density filter. Passengers distributed through multiple modes and entry nodes can reduce congestion at a single point. Conversely, fragmented TOD can create queues at drop-off areas, terminal entrances, and initial screening zones.

Passenger and Baggage Integration

Airport terminals have two main flows that must be managed simultaneously: the human flow and the goods or baggage flow. Passenger flow requires clear orientation, spatial comfort, safety, and short processing time. Goods and baggage flow requires sorting accuracy, security, and connectivity with logistics systems. If the two flows intersect without a clear separation strategy, the risk of circulation obstruction will increase.

Vertical circulation separation is one design approach that can reduce conflicts between passenger and baggage movement. In this approach, goods and baggage can be placed at a lower level through an Automated Baggage Handling System. In contrast, the main level is focused on passenger movement, commercial areas, waiting lounges, and intermodal connections.

METHOD

This study uses a descriptive quantitative approach. The research object is the design criteria for Terminal 4 of Soekarno-Hatta Airport within the context of a TOD area. The research population consists of airport users who have experience using terminal facilities at Soekarno-Hatta Airport. The sample was determined using purposive sampling based on the consideration that respondents had direct experience with departure, arrival, and mode-transfer processes in the airport area.

The questionnaire was distributed digitally to 120 respondents and produced 100 valid responses for analysis. The research instrument used a five-point Likert scale, where 1 = strongly disagree and 5 = strongly agree. For the design-criteria model, the average Likert values were normalized into expectation scores ranging from -1 to 3 using the conversion approach: expectation score = Likert mean - 2. With this conversion, a score of 0 indicates a neutral position, a positive score indicates a design need perceived as important, and a negative score indicates a criterion that is not yet considered to support terminal performance.

The independent variables in this study consist of five criteria: smart airport digital (a), good connectivity (b), passenger and baggage integration (c), safety (d), and comfort (e). The smart airport digital variable includes IoT, smart signage, self-service, and indoor navigation applications. The good connectivity variable includes intermodal accessibility, terminal connectivity, and pedestrian comfort. The passenger and baggage integration variable includes check-in speed, baggage handling, and bottleneck reduction. The safety variable includes building protection and user safety, while the comfort variable includes spatial experience quality, facility location, and clear separation between zones.

Data analysis was conducted through validity testing, reliability testing, descriptive statistics, and the synthesis of a conceptual mathematical model. Validity testing used the Pearson Product-Moment correlation at a 5% significance level. Based on 100 valid respondents, the r-table value is approximately 0.195. An instrument is considered valid if the r-count is higher than the r-table value. Reliability was measured using Cronbach's Alpha, with a minimum threshold of 0.60.

The mathematical model used in this study is a third-order polynomial model: $y = ax^3 + bx^2 + cx + (d+e)$. The variable y represents the design quality index, while x represents the normalized passenger load in units of thousands of passengers per hour. This model is not positioned as a causal regression model, but rather as a conceptual-predictive model for reading design sensitivity based on user-perception weights. Therefore, the model functions as a design-support tool that helps designers translate user priorities into spatial strategies and terminal connectivity systems.

https://doi.org/10.53067/ijomral.v5i5.502

RESULTS AND DISCUSSION

Validity and Reliability of the Instrument

The instrument testing results show that all questionnaire items had r-count values above the r-table value; therefore, all indicators were declared valid. The Cronbach's Alpha value obtained was 0.824. This value is above the minimum threshold of 0.60, indicating that the instrument is reliable and appropriate for measuring user perceptions of Terminal 4 design criteria.

The validity and reliability of the instrument indicate that the respondents' answers can be used to identify tendencies in design priorities. In architectural research, this is important because terminal criteria are not only measured through technical standards, but also through the experiences of users who directly perceive movement processes within the airport area.

Priority of Design Criteria

The score tabulation shows that comfort obtained the highest score at 2.27. However, within the connectivity criteria group, smart airport digital became the main priority with a score of 2.23, followed by good connectivity with a score of 1.99. This indicates that users require a terminal that is not only physically comfortable, but also capable of providing fast information, orientation, and service processes through digital systems. The detailed design-criteria scores are presented in Table 1.

Table 1. Terminal 4 design criteria scores based on user perception

Symbol	Criterion	Scope	Score	Interpretation
a	Smart airport digital	IoT, smart signage, self-service, digital navigation	2.23	Digital accelerator
b	Good connectivity	TOD integration, intermodal access, pedestrian movement, travel distance	1.99	Physical area integration
c	Passenger and baggage integration	Check-in, baggage, logistics flow, bottleneck reduction	1.59	Circulation efficiency
d	Safety	Safety, building protection, access control	1.97	Basic design constant
e	Comfort	Spatial quality, orientation, facilities, user experience	2.27	Spatial experience constant

Source: Author's analysis, 2026

The high score for smart airport digital indicates that users place information systems and automation as core requirements for future terminals. In terminals with large passenger loads, digital technology can help disperse queues and reduce spatial uncertainty. Examples include real-time information regarding gate positions, walking-time estimates, screening queue status, flight schedules, and baggage status.

The good connectivity score of 1.99 indicates that intermodal integration is an important criterion in Terminal 4 development. Users require concise transfers from airport rail, buses, drop-off areas, parking facilities, and the terminal. Therefore, terminal design must avoid overly long transfer distances and confusing meeting points.

The passenger and baggage integration score of 1.59 was the lowest among the variables. This value indicates that the integration of human and goods flows remains a vulnerable point. In the design of Terminal 4, this finding should be translated into strategies for vertical circulation separation, baggage automation, and the control of meeting points among passengers, goods, and service vehicles.

Synthesis of the Mathematical Model of Design Performance

The mathematical model was used to assess the sensitivity of design performance to increasing passenger load. In the peak-load simulation of 11,000 passengers per hour, the value of x was normalized to 11. The model coefficients use the user-expectation scores, namely a = 2.23, b = 1.99, and c = 1.59. In this simulation scenario, coefficients d and e were assigned the maximum value of 3 as baseline operational standards for safety and comfort in an international terminal context.

The model calculation is expressed as follows: $y = ax^3 + bx^2 + cx + (d+e)$. By substituting x = 11, the equation becomes $y = 2.23(11^3) + 1.99(11^2) + 1.59(11) + (3+3)$.

Therefore :

y = 2.45(1.331) + 2.20(121) + 21.45 + 3

y = 2.968,13 + 240,79 + 17,49 + 6

y = 3.232,41

The result shows that the smart airport digital component makes the largest contribution within the model structure, particularly because it is placed in the cubic coefficient. This should not be interpreted as singular causal evidence, but as an indication that under peak-load conditions, the digital system is the most sensitive factor in maintaining terminal performance. The digital system needs to function as an accelerator that speeds up processes, directs passengers, and reduces pressure on physical space.

https://doi.org/10.53067/ijomral.v5i5.502

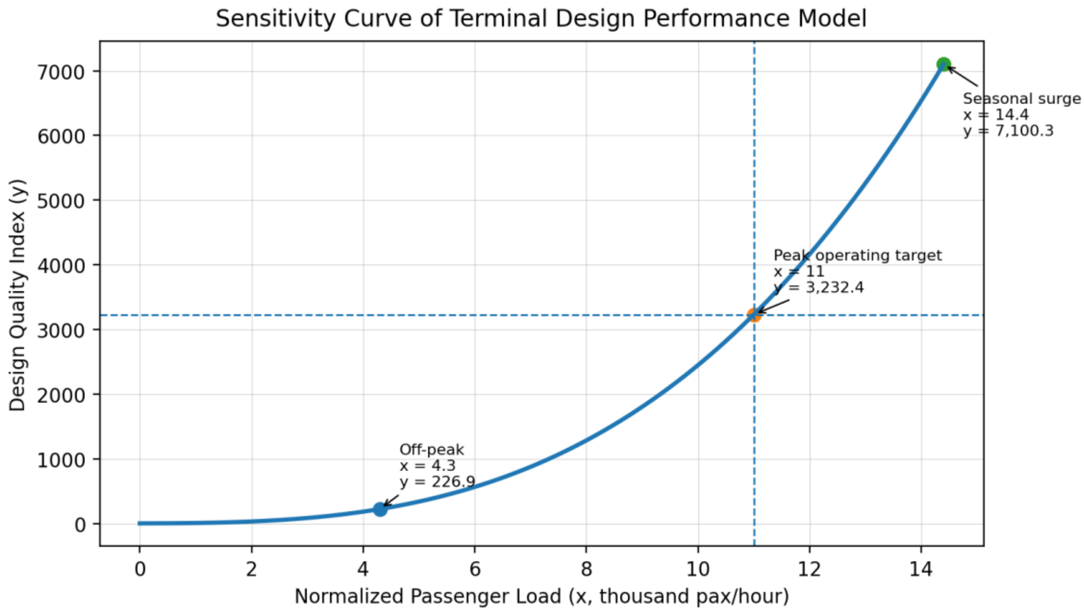

Figure 1. Sensitivity curve of the Terminal 4 design performance model

Source: Author's analysis, 2026

Design Implications for Terminal 4

The research findings indicate the need for a phygital design approach, namely the integration of physical spatial strategies and digital systems. In physical design, Terminal 4 is recommended to use a radial or centralized configuration so that the travel distance from the TOD hub to processing areas and gates can be minimized. This configuration can reduce the excessively long directional spread commonly found in linear configurations.

On the digital side, the terminal should be equipped with smart wayfinding connected to mobile applications, interactive information screens, density sensors, and travel-time estimation systems. Passengers do not only read static signs, but also receive information that corresponds to their position and individual flight schedules. This is important for creating a seamless journey from the moment passengers arrive in the airport district until they enter the aircraft.

Figure 2. Smart airport application scheme

Source: Author's analysis, 2026

In relation to passenger and baggage integration, this study recommends vertical circulation separation. Goods and baggage flows should be placed on a lower level through an Automated Baggage Handling System. In contrast, the main level is dedicated to passenger movement, check-in areas, screening, waiting lounges, and commercial areas. This strategy can reduce conflicts between flows and improve the clarity of spatial organization.

TOD integration needs to be realized through a compact intermodal hub. This hub must directly connect airport rail, buses, drop-off areas, parking, ride-hailing transportation, and pedestrian routes with the terminal. At these meeting points, biometric gates, self-baggage drop, and smart queue systems can be positioned as queue-dispersal nodes before passengers enter denser terminal zones.

Safety and comfort remain basic requirements. The high comfort score indicates that digital systems should not replace spatial quality. The terminal still requires natural lighting, proper ventilation, comfortable materials, sufficient seating areas, easily accessible toilets, and clear separation among public, semi-sterile, and sterile areas.

Research Limitations

This study has limitations in using user-perception data as the basis for model weighting. The resulting mathematical model is conceptual-predictive and does not replace actual movement simulation. Therefore, the model needs to be further validated using dynamic simulation, such as agent-based modeling, MassMotion, or AnyLogic, especially to test travel time, spatial density, and queue capacity under various passenger-load scenarios.

Another limitation is the absence of direct measurements of automated baggage performance, actual check-in time, and passenger arrival patterns based on flight schedules. These data are important for strengthening the model in future research.

CONCLUSION

The mathematical model produced in this study not only functions as a quantitative analytical tool, but can also serve as a design-support basis for architects in the decision-making process. Through this model, user-perception priorities regarding smart airport digital systems, TOD integration, comfort, safety, and passenger-baggage integration can be translated into more measurable design directions. Thus, architects do not design terminals solely based on spatial intuition or minimum technical standards, but also based on systematically analyzed user needs. The model can help determine design strategies such as radial mass configuration, the placement of an intermodal hub, smart wayfinding systems, vertical circulation separation, and the integration of digital technology into terminal space. Therefore, this mathematical model can be positioned as an architectural design-support instrument for creating Terminal 4 of Soekarno-Hatta Airport as a more

https://doi.org/10.53067/ijomral.v5i5.502

efficient, adaptive, human-centered, and responsive terminal within the complexity of passenger and goods movement in a TOD area.

The score results show that smart airport digital obtained a value of 2.23 and good connectivity obtained a value of 1.99. These two variables indicate high user expectations for real-time information systems, process automation, digital navigation, and intermodal integration. Meanwhile, comfort obtained a score of 2.27, confirming that the quality of spatial experience remains an important foundation in terminal design.

The mathematical model $y = ax^3 + bx^2 + cx + (d+e)$ produced a design quality index of 3,232.41 in the peak-load simulation at $x = 11$, using maximum baseline constants for safety and comfort. The model structure indicates that smart airport digital becomes the most dominant component in maintaining terminal performance under high-load conditions. At the same time, TOD integration acts as a buffer against physical density in the airport area.

Architecturally, this study recommends implementing a radial or centralized configuration, smart wayfinding, biometric gates, self-baggage drop, smart queue systems, a compact intermodal hub, and vertical separation between passenger and baggage circulation. These recommendations are directed toward creating Terminal 4 as an efficient, safe, comfortable, navigable, and human-centered airport terminal.

Figure 3. Architectural design recommendation

Source: Author's analysis, 2026

Future research is recommended to conduct dynamic movement simulations based on the terminal plan to validate the perception-based model developed in this study. Further studies may also incorporate energy sustainability, green airport strategies, and more detailed integration of smart technology with airport operational systems.

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