

Article

Cultural Diversity and the Operational Performance of Airport Security Checkpoints: An Analysis of Energy Consumption and Passenger Flow

Jacek Ryczyński ^{1,*} , Artur Kierzkowski ^{1,*} , Marta Nowakowska ² and Piotr Uchroński ³ ¹ Department of Technical Systems Operation and Maintenance, Faculty of Mechanical Engineering, Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland² Department of Management Systems and Organisation Development, Faculty of Management, Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland; marta.nowakowska@pwr.edu.pl³ Department of Transport and Information Technology, WSB University, Zygmunta Cieplaka 1C, 41-300 Dąbrowa-Górnica, Poland; puchronski@wsb.edu.pl

* Correspondence: jacek.ryczyński@pwr.edu.pl (J.R.); artur.kierzkowski@pwr.edu.pl (A.K.)

Abstract

This paper examines the operational consequences and energy demands associated with the growing cultural diversity of air travellers at airport security checkpoints. The analysis focuses on how an increasing proportion of passengers requiring enhanced security screening, due to cultural, religious, or linguistic factors, affects both system throughput and energy consumption. The methodology integrates synchronised measurement of passenger flow with real-time monitoring of electricity usage. Four operational scenarios, representing incremental shares (0–15%) of passengers subject to extended screening, were modelled. The findings indicate that a 15% increase in this passenger group leads to a statistically significant rise in average power consumption per device (3.5%), a total energy usage increase exceeding 4%, and an extension of average service time by 0.6%—the cumulative effect results in a substantial annual contribution to the airport's carbon footprint. The results also reveal a higher frequency and intensity of power consumption peaks, emphasising the need for advanced infrastructure management. The study emphasises the significance of predictive analytics, dynamic resource allocation, and the implementation of energy-efficient technologies. Furthermore, systematic intercultural competency training is recommended for security staff. These insights provide a scientific basis for optimising airport security operations amid increasing passenger heterogeneity.

Keywords: energy consumption; operational performance; culture differences awareness; airport security screening checkpoints; passenger flow; carbon footprint; social aspects



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1. Introduction

The contemporary civil aviation sector operates within an increasingly complex global context, marked by intensified globalisation, the growing internationalisation of passenger flows, and the evolution of asymmetric threats, including terrorism, cyberattacks, and transnational crime. In such a dynamic and multidimensional operational environment, ensuring the effectiveness of aviation infrastructure protection systems requires advanced technological capabilities, procedural flexibility, and the systematic integration of socio-cultural determinants. Passenger security screening protocols—a core component of the aviation security architecture—must respond not only to threat detection requirements but

also to growing expectations regarding operational efficiency, procedural ergonomics, and energy resource optimisation.

In this context, cultural factors—including social norms regarding physical contact, religious practices influencing clothing, linguistic barriers that impede communication, and divergent perceptions of technology—can significantly impact the course of screening procedures. Cultural differences may affect the frequency of security officer interventions, passenger processing times, and the likelihood of alternative methods being employed (e.g., manual searches or explanatory dialogues), leading to increased infrastructure load and elevated energy demand associated with detection technologies [1,2].

From an institutional perspective, the International Civil Aviation Organisation (ICAO), in its *Global Aviation Security Plan* [1], explicitly emphasises the necessity of incorporating cultural considerations into national aviation security frameworks. Security culture is defined therein as a collective set of beliefs, values, and organisational practices that shape the implementation of protective measures, with its proper cultivation regarded as a prerequisite for the effective execution of preventive actions in an international operating environment [3].

Operational experience demonstrates that failure to align security procedures with local and regional cultural contexts may result in a heightened risk of interpersonal conflict, reduced passenger satisfaction, and substantial reductions in airport operational efficiency. Empirical evidence from sub-Saharan African airports confirms a correlation between culturally insensitive procedures, increased demand for secondary screening, and excessive loads placed on energy infrastructure [4].

In response to these challenges, numerous airports have adopted diversity, equity and inclusion (DEI) strategies that include intercultural training for security personnel, inclusive recruitment practices, the provision of private screening areas for culturally sensitive passengers (e.g., those wearing religious garments), and the deployment of alternative communication tools such as visual instructions, automated translators, and multilingual passenger information systems. For instance, airports in the Gulf region have implemented operational training programmes comprising modules on intercultural communication, conflict resolution, and religious awareness [5].

The present study aims to analyse the impact of cultural factors on selected performance parameters of airport security screening checkpoints, with a particular focus on two operational dimensions: (1) checkpoint throughput (measured as the number of passengers processed per unit of time) and (2) energy consumption of screening equipment. The research employs methodological triangulation, combining empirical data analysis, operational scenario modelling, and an in-depth review of domain-specific literature. The findings aim to inform strategic recommendations for designing culturally responsive and energy-efficient security systems, thereby contributing to improved quality and sustainability in global aviation security management.

2. Background

Following the current legal framework of the European Union, particularly Commission Implementing Regulation (EU) 2025/920 and its annexes, passenger security screening constitutes a fundamental element of the civil aviation security system. Its principal function is preventive, aimed at mitigating risks related to acts of unlawful interference. The primary purpose of security screening is to detect and prevent the introduction of prohibited items—including explosives, firearms, and other devices or substances as defined by international and European regulations—into aircraft cabins or security-restricted areas of airports. By ensuring the effective identification and interception of such prohibited articles, the screening process safeguards the integrity and security of civil aviation operations.

Security screening procedures are clearly defined and encompass manual searches, walk-through metal detectors (WTMD), hand-held metal detectors (HHMD), trace detection systems (ETD), non-ionising millimetre-wave body scanners (BS), footwear screening devices (SMD and SED), and specially trained canine units. Equivalent provisions apply to the screening of cabin baggage, particularly concerning liquids, aerosols, and gels (LAGs), which must be carried in transparent, regulation-compliant bags and analysed using dedicated liquid screening technologies or C2/C3 scanning systems capable of assessing contents without unpacking. Details are presented in Figure 1.

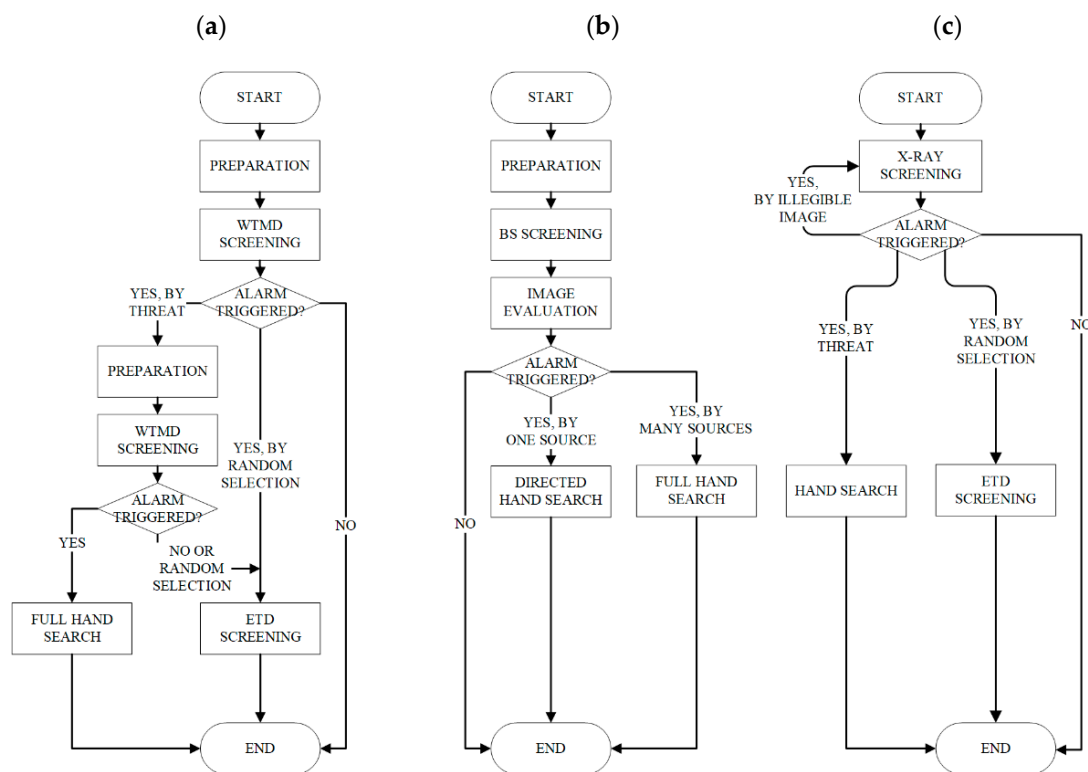


Figure 1. Organisation of airport security screening checkpoints: (a) Passenger screening procedure using WTMD technology; (b) Passenger screening procedure using body scanner technology; (c) Cabin baggage screening procedure.

Although the regulatory framework is unambiguous, the operational implementation of these procedures encounters significant challenges stemming from the increasing cultural, religious, and linguistic diversity of passengers.

Considerations such as the protection of personal dignity, the need for privacy, divergent social norms concerning physical contact, and differing perceptions of technology all influence both the conduct and perception of security screening processes. Manual screening is a highly sensitive activity. While functionally necessary, it demands a high degree of interpersonal skill, empathy, and cultural awareness from security staff.

For individuals wearing traditional or religious garments (e.g., galabiyas, hijabs, turbans, saris), screening must be conducted in the least invasive manner possible, with full respect for cultural norms. Where necessary, this includes providing a private screening area and assigning an officer of the same gender. Such considerations are also critical in situations where religious doctrine prohibits physical contact with members of the opposite sex—non-compliance in these contexts may be perceived as a violation of fundamental human rights.

Language barriers present an additional operational challenge. A lack of common language, differences in writing systems, or limited communicative ability on the part of

the passenger can substantially hinder the effectiveness of screening procedures. In such cases, the use of visual aids, pictograms, multilingual information cards, and—at high-capacity airports—interactive information systems and cultural interpreters is strongly recommended. Security screening officers (SSOs) must be equipped to employ non-verbal communication techniques and to interpret signs of discomfort resulting from cultural misunderstanding rather than wilful non-compliance.

Passenger perceptions of technology further influence screening efficiency. Individuals from certain cultural backgrounds may be apprehensive about using body scanners, perceiving them as invasive or potentially harmful. In these instances, transparent and informative communication is essential, including an explanation of the device's function, assurance of health and privacy safeguards, and the option to undergo an alternative procedure (e.g., manual search). Although such accommodations may increase screening time, they foster trust and significantly reduce the risk of conflict.

All the aforementioned factors directly impact checkpoint throughput, human resource allocation, energy consumption, and the overall operational efficiency of airport terminals. In response, many airports are implementing policies that integrate intercultural components into their security operations. For example, Schiphol Airport in Amsterdam has introduced comprehensive training on cultural diversity and bias mitigation, resulting in a reduction in passenger complaints and an improvement in satisfaction indicators. Toronto Pearson International Airport has adopted a “culturally responsive screening” model featuring cultural interpreters, private screening facilities, and multilingual visual communication. Similar initiatives have been implemented at airports in Singapore, Tokyo, and Helsinki, with a strong emphasis on predictive passenger flow management and real-time operational support.

These efforts are often embedded within broader DEI strategies, which are gaining prominence across the civil aviation security sector. Organisations such as the International Air Transport Association (IATA) and ICAO have emphasised the importance of embedding diversity into human resources and service delivery frameworks. A notable example is IATA's “25by2025” initiative, which aims to increase female representation in aviation leadership roles by 2025. In the security context, DEI strategies encompass cultural competence training, merit-based recruitment, fostering inclusive workplace environments, and ongoing procedural audits to ensure fairness and non-discrimination. One of the primary arguments for adopting Diversity, Equity, and Inclusion (DEI) in aviation security is enhanced risk management: culturally and cognitively diverse teams are more likely to engage in critical thinking, identify emerging threats more rapidly, and respond adaptively under pressure.

3. Literature Review

The literature review is divided into three thematic sections: energy consumption in airport terminals, operational effectiveness of security screening procedures, and the influence of cultural factors on transportation systems, including aviation. While each of these areas is well-represented in the literature, there is a lack of studies that examine the links and interactions between them, particularly in the context of airport security operations. This review highlights existing findings within each theme, identifies their limitations, and synthesises evidence to show where these domains intersect. The section concludes by specifying the research gap and justifying the need for an integrated empirical investigation.

3.1. Energy Consumption

Energy efficiency has become an increasingly important topic in contemporary air transport research, particularly in the context of sustainable development. One emerging and still relatively underexplored domain concerns energy usage within airport security control zones. Despite the growing relevance of this issue, most existing studies have so far focused on broader airport facilities, including passenger terminals [6] and apron operations [7], while omitting the specific characteristics of the security checkpoint environment.

Available predictive models for estimating airport energy consumption incorporate variables such as passenger volume [8], outdoor air temperature [9], and flight schedules [10], offering a comprehensive view of energy demand at the macro level. Ortega Alba and Manana [11] conducted a thorough review of the literature addressing energy-related aspects in aviation, contributing to a foundational understanding of key operational and environmental drivers. Furthermore, Lin et al. [12] have explored the efficiency of heating, ventilation, and air-conditioning (HVAC) systems, examining passenger flows within various terminal areas, including the check-in, departure, and security control zones.

The terminal itself has also been subject to investigations from an energy perspective, particularly in terms of its architectural and functional configuration [13,14]. However, few publications offer detailed assessments of how the layout and operation of security checkpoints specifically influence electricity consumption. Research in this field has demonstrated that energy savings can be achieved through the optimised management of airport security control points [15]. Subsequent studies have further confirmed that both the structural layout and the way these zones operate can significantly contribute to reducing overall power consumption [16].

Operational performance is not determined solely by the physical configuration of systems. The human factor, particularly the experience and procedural competence of security control officers (SCOs) and supporting personnel, has also been shown to influence energy efficiency outcomes [17,18]. These insights point to the need for a more integrated research approach—one that encompasses both technical systems and human operational practices.

In summary, although a growing body of research has addressed energy usage at airports in general, there is still a lack of focused studies on the specific energy consumption characteristics of security screening areas. Considering the potential for reducing electricity demand while maintaining the effectiveness and safety of security operations, further investigation in this area appears warranted. It may offer meaningful benefits for both operational efficiency and sustainability.

3.2. Operational Efficiency

As air travel grows, airport security control zones face increasing pressure due to rising passenger volumes, directly impacting operational efficiency. Numerous studies have consistently identified the security screening process as a critical bottleneck within the broader passenger service system [19]. Addressing this issue requires a multifaceted approach, with research exploring procedural and technological improvements.

A significant body of literature has proposed various strategies to improve process throughput and reduce queue times. Behavioural analysis is among the techniques frequently cited, offering the potential to optimise passenger flow through predictive and adaptive control. Ploch and Žihla [20] identified ten factors influencing security control performance: system reliability, operational complexity, and the human factor. Meanwhile, Marshall et al. [21] utilised a proportional-integral-derivative (PID) control model to simulate queue behaviour, resulting in a 12% reduction in average waiting time. Simulation and optimisation methods also play a key role in resource allocation. For example, Adacher and Flamini [22] developed a decision-support module based on simulation to minimise costs

related to both passenger satisfaction and resource management, particularly regarding checkpoint allocation. Modelling techniques such as discrete event simulation [23], Petri nets [24,25], and queueing theory [23,26] are increasingly applied to refine control system architecture and predict congestion patterns.

The integration of advanced detection technologies has proven equally vital to operational efficiency. Hättenschwiler et al. [27] demonstrated the value of explosive detection systems for cabin baggage (EDSCB) in improving screening accuracy. Similarly, improvements in throughput have been observed when systems are properly configured and equipped with explosive trace detection (ETD) devices. The configuration and sensitivity of detection systems can also influence performance outcomes, as shown in studies by Sterchi and Schwaninger [28].

Operational strategies also benefit from a detailed understanding of procedural variables. Studies by Abdulaziz Alnowibet et al. [29] and Rodríguez-Sanz et al. [30] examined the impact of passenger processing time and the number of active desks on performance. Liu et al. [31] assessed factors such as access point capacity, average passage duration, and staff workload. Kierzkowski [32] introduced a framework that considers lane hierarchy and system capacity, while Skorupski et al. [33] focused on parameters such as baggage status assignment probability and X-ray screening times for checked luggage. Nikolaev et al. [34] suggested evaluating system effectiveness based on either the rate of successful detection of prohibited items or the processing speed of low-risk individuals.

Innovative management approaches have also been applied to improve efficiency. For example, dynamic allocation systems for check-in desks have been shown to stabilise passenger waiting times at security checkpoints when managed centrally. Adacher et al. [35] utilised a surrogate-based optimisation algorithm to determine the optimal number of security lanes.

Though not exclusive to security control, Koryakina et al. [36] presented a geographic information system concept intended to accelerate emergency response decisions across the airport environment. This illustrates the broader trend toward integrating decision-support systems to enhance real-time operational agility. Striking a balance between security and efficiency remains a central challenge. While efforts focus on reducing screening duration and queue length, strict security standards must still be upheld. Proactive and adaptive security management strategies are increasingly seen as necessary to reconcile these competing objectives [37,38].

3.3. Cultural Factors in Transportation Systems

Cultural factors have a notable impact on user behaviours and the operational dynamics of transportation systems. Their influence extends not only to mode choice preferences but also to how individuals perceive and interact with transportation infrastructure. Nahiduzzaman et al. [39] highlighted that, in Saudi Arabia, the use of public transport is significantly stigmatised due to concerns over privacy and cultural norms associated with social status, particularly about gender roles. Similarly, Hansson et al. [40] observed that passenger preferences for regional public transportation are influenced by cultural values related to comfort and the coordination of transportation networks.

Merritt and Maurino [41] emphasise that these “cultural interfaces” are asymmetrically biased toward Western models—particularly those of the United States and Western Europe—and that unexamined cultural assumptions can introduce hidden risks to safety and efficiency. When operational protocols fail to account for differences in communication styles, power distance, or decision-making norms, routine tasks such as boarding, security screening, and cabin services can become inefficient or prolonged, resulting in increased energy demands from systems like lighting, climate control, and baggage han-

dling. Broom [42] argues that while security processes have matured with strong cultural integration, security operations continue to lag. Implementing a strong security culture—through targeted recruitment strategies, professional development, and mission-oriented training—can improve staff retention and efficiency by reducing unnecessary procedural delays (and thus energy consumption) at security checkpoints. By treating safety as a distinct cultural domain rather than an adjunct to safety, airports can improve staffing levels and workflows by reducing idle scanners, lighting, and ventilation systems.

Recent empirical research supports this link between cultural heterogeneity and energy use. Wieszala et al. [43] surveyed flight crews at multiple airlines and found that misunderstandings due to language dialects or differing assumptions about safety postures often delayed coordinated team actions. Such delays, whether in security checks or maintenance procedures, force auxiliary systems to remain fully powered for more extended periods, resulting in measurable spikes in electrical consumption. Their recommendation to standardise language and conduct regular cross-cultural training directly addresses these inefficiencies by promoting a common operational lexicon that speeds task completion.

Essential subcultural differences within job groups can further modulate energy profiles. Chan, Li, and Braithwaite [44] demonstrate that pilot attributions of accident causation vary significantly based on their initial background (i.e., airline-sponsored, self-funded, or ex-military). These perceptual discrepancies shape how crews prioritise and implement safety controls. Groups more attuned to causal sequences at the organisational level tend to follow hierarchical procedures, which, while accurate, can increase system downtime for ground support equipment and require supervisory approval before shutting down support units. On the other hand, crews emphasising “preconditions for unsafe action” at the individual level often implement more decentralised rapid response measures, reducing system uptime. Awareness of these subcultural tendencies allows airlines to tailor training and procedure design, optimising energy-dependent tasks for both safety and efficiency. Passenger perceptions of safety controls also reflect cultural values and influence operational efficiency. Stotz et al. [45] investigated the acceptability of risk-based security checks by examining perceived costs and benefits among travellers. Their findings indicate that while low-risk passengers appreciate shorter wait times, common concerns about fairness and perceived security limit acceptance. In culturally diverse environments, such perceptions can lead to resistance to new security protocols, resulting in process bottlenecks and increased system idle times (e.g., open scanners and longer use of lighting). Addressing these cultural acceptability issues through clear communication and participatory design can mitigate such energy-related inefficiencies.

Cultural context also manifests at organisational and team levels. Strauch [46] highlighted the impact of culturally influenced cognitive and perceptual styles on the performance of teams operating under stress—conditions typical in critical transport infrastructure. Choudhry [47] showed that aviation maintenance technicians (AMTs) do not always conform to culturally stereotypical behaviours, which can have important implications for operational safety. Brito Neto [48] argued that transformational leadership strategies are a prerequisite for effective collaboration within multicultural team management. Intercultural communication remains a key dimension of analysis. Liao [49] documented substantial differences between Chinese and Western pilots regarding safety issue reporting, attributable to divergent values such as social harmony and power distance. Kale et al. [50] investigated pragmatic barriers to communication between pilots and air traffic controllers, particularly under stress, revealing the risks of miscommunication. Similar issues affect the maritime sector, where communication styles and hierarchical structures are also culturally conditioned [51].

From an ergonomic perspective, Al Wardi et al. [52] identified ergonomic incompatibilities experienced by Middle Eastern aircrews operating aircraft designed according to Western anthropometric standards—factors that directly impact comfort and operational safety. In a subsequent study, Al Wardi [53] argued that widely adopted error classification systems such as HFACS may embed cultural biases and should be regionally adapted. Keller et al. [54] stressed the importance of accounting for cultural variation in aviation training programmes, while Metscher et al. [55] demonstrated the effectiveness of culturally responsive crew resource management (CRM) training in enhancing operational safety.

Culture also moderates demographic variables. Carlsson-Kanyama [56] reported gender-based differences in travel patterns and CO₂ emissions, which, by Khan [57], were amplified during the COVID-19 pandemic. Higuera-Castillo [58] further explored how national value systems influence the adoption of sustainable transportation modes, such as electric vehicles, underlining the necessity of culturally informed transportation policy.

Despite a robust body of literature addressing cultural influences in transport, a clear research gap remains concerning the impact of cultural variables on civil aviation security screening systems. As noted by Wood and Raj [59], these procedures are often perceived as discriminatory by ethnic minorities. Pratama [60] warned that neglecting cultural nuances in the design of screening protocols may result in inefficient resource utilisation. Fredrikson and Laporte [61] underscored the role of security culture as a determinant of adaptability and procedural effectiveness in aviation security systems. However, this domain remains under-researched and calls for systematic, empirical inquiry to assess the operational and throughput implications of culturally differentiated screening procedures.

A critical review of the literature reveals that research on airport security processes is largely compartmentalised, with most studies focusing on either operational performance, energy management, or socio-cultural aspects in isolation. Comprehensive analyses that explicitly address the trade-offs and synergies between maintaining high security standards and improving energy efficiency remain rare. As a result, there is limited empirical evidence to inform best practices that balance these sometimes-competing objectives.

3.4. Research Gap

Although recent studies acknowledge the need for more integrated approaches to airport security screening, the literature lacks a systematic comparison of existing findings. There is an absence of empirical research that directly addresses unresolved questions, such as: To what extent can energy-saving measures be implemented in security zones without compromising regulatory compliance or operational effectiveness? What is the quantifiable impact of culturally responsive practices on system efficiency and security outcomes? Addressing these gaps is crucial for developing evidence-based guidelines that co-optimize security, efficiency, and sustainability in airport operations.

Despite the growing operational and policy-level recognition of the relevance of cultural determinants within security screening processes—and the concurrent implementation of practical measures aimed at mitigating their adverse effects, such as multilingual communication tools, adaptive protocols for culturally distinct passenger groups, and structured intercultural competence training—existing practices remain largely intuitive, reactive, and insufficiently grounded in empirical research.

There is a lack of quantitatively operationalised studies that systematically and comparatively examine the impact of culturally responsive screening mechanisms on key performance indicators within airport security operations, such as throughput capacity, staff resource allocation, energy consumption of screening technologies, and overall system efficiency. To date, the literature has primarily focused on qualitative analyses of passen-

ger experiences or descriptive accounts of best practices, often excluding operational and environmental dimensions from the scope of investigation.

Considering the above, the present study offers a substantive contribution to the existing literature by providing the first integrated attempt to empirically analyse the effects of cultural variables and the procedural adaptations made in response on the operational performance of airport security screening systems. By applying methodological triangulation—including the analysis of passenger flow metrics, energy efficiency of screening devices, and scenario-based modelling of culturally sensitive service configurations—this article addresses a critical research gap at the intersection of cultural competence, operational logistics, and civil aviation infrastructure protection.

4. Methodology

The present study aimed to investigate the impact of cultural factors on the operational efficiency and energy consumption of airport security screening systems, with particular emphasis on differences in the handling of passengers requiring enhanced screening. The research was experimental and was designed to account for both the technical parameters of screening devices and the behavioural aspects of passenger flow.

4.1. Research Environment

The study presented in the article was conducted at the largest regional airport in southern Poland, serving an average of 4000 passengers per day. Data were collected from January to March 2025 during peak hours (6:00–10:00 and 16:00–20:00) to account for the maximum variability of passenger flow. The sample consisted of a total of 660 passengers, divided into four scenario groups: 171 in the first and second scenarios (“0% and 5% enhanced”, respectively), 164 in the third scenario (“10% enhanced”), and 154 in the fourth scenario (“15% enhanced”). Research on the impact of the cultural and religious diversity of passengers on the throughput of the airport security control system was conducted in the form of an observational study in a real operational environment. The study systematically observed the behaviour of passengers while passing through security checkpoints, with particular emphasis on their reactions to standard procedures such as removing shoes, passing through detection gates, and undergoing body searches.

The study employed an original method for measuring energy consumption, drawing on existing literature on monitoring operational infrastructure. Energy consumption sensors recorded real-time consumption of scanning equipment, correlated with passenger ID. All data collection and storage procedures received a positive opinion from the university ethics committee. Passengers were informed about the study and had the opportunity to refuse participation. CCTV recordings were used only to record the time and number of operations, not to identify individuals. All materials were deleted after the analysis was completed.

The procedure for implementing four different scenarios (0%, 5%, 10% and 15%) adopted in this study is based on the results of previous studies on the effectiveness of manual procedures and international safety standards. Studies [17,18,62,63] have shown that under normal conditions, approximately 10–15% of travellers require personal checks or additional manual procedures. Since, in our model, we already assumed a starting level of 10% of mandatory inspections (following [64,65]), it was reasonable to introduce an “extended” scenario at the level of 15%, which corresponds to the upper limit recommended in the literature and allows for examining the actual impact of reinforced procedures, taking into account the cultural factor, on energy consumption.

4.2. Research Description

In the initial stage, energy consumption monitoring devices were installed at three key security screening points: the walk-through metal detector (WTMD), the X-ray baggage scanner, and the explosive trace detection (ETD) device. Measurements of energy consumption were temporally synchronised with a system recording the progression of passenger processing, thereby enabling precise correlation between energy use, device activity, and passenger traffic intensity.

The analysis of energy consumption revealed that the WTMD consumes a constant amount of energy regardless of whether a passenger is passing through or the device is in standby mode. In contrast, the X-ray and ETD devices exhibit variable energy consumption, with higher values during active scanning and lower values during periods of inactivity, as detailed in Table 1.

Table 1. Energy consumption of devices supporting the security screening process.

Mode	Energy Consumption [W]		
	HI-SCAN 6040aTiX	CEIA HI-PE Plus	Smiths Detection IONSCAN 600
X-ray idle *	1013	-	-
X-ray move **	1136	-	-
X-ray scan	2125	-	-
WTMD	-	95	-
ETD idle	-	-	55
ETD scan	-	-	155

* X-ray scanner sleep mode—both lamp and roller conveyor in sleep mode; ** X-ray scanner move mode—lamp in sleep mode, roller conveyor working.

This differentiated energy profile underscores the importance of distinguishing between device operating states when evaluating the energy efficiency of the security screening system.

To examine the impact of a heterogeneous passenger composition on system performance and energy consumption, a model involving passenger proxies (statistical actors) was employed. These proxies were introduced into the security screening queue to represent groups requiring enhanced screening due to cultural or religious attire or behaviour, such as individuals wearing burkas or turbans. To maintain a realistic passenger flow and simulate system loads ranging from 85% to 100% of nominal capacity, the proportion of passengers requiring enhanced screening in the test stream did not exceed 15%. Four different scenarios were analysed. The base scenario was a scenario in which there were no passengers requiring special procedures due to cultural or religious differences. In the remaining three scenarios, the share of such passengers in the serviced stream was 5%, 10% and 15%, respectively. At the outset, proxies representing different categories were introduced evenly; in subsequent phases, individual groups were isolated to precisely determine the effect of specific cultural factors on system parameters.

Data collection was conducted with one-minute resolution, recording the following variables: the number of passengers within the security screening system, the number of passengers requiring enhanced screening, the number of individuals awaiting screening, and the real-time energy consumption of the screening devices. Additionally, statistical data aggregation was performed every 15 min, allowing for the analysis of changes in passenger flow intensity and energy use across periods with varying loads.

The empirical analysis included the correlation between the percentage share of passengers requiring enhanced screening and changes in checkpoint throughput, as well as energy consumption per passenger. The results enabled the modelling of operational

scenarios that accounted for cultural diversity in passenger flows and their effect on the energy and logistical efficiency of the security screening system.

An integral element of the methodology was the consideration of human factors, specifically the competence and behaviour of security screening personnel. Cultural awareness and interpersonal skills of officers were regarded as essential for the proper implementation of procedures tailored to the needs of various passenger groups. The study employed methodological triangulation, combining quantitative data, qualitative observations, and computer simulations, which yielded a comprehensive perspective on the phenomenon under investigation.

The described research methodology ensures a high degree of reliability and validity of the obtained results, providing a robust foundation for the formulation of operational and strategic recommendations aimed at optimising the functioning of airport security screening systems, with full consideration of cultural aspects and energy efficiency.

5. Results and Discussion

The conducted study demonstrated that the proportion of passengers requiring enhanced security screening exerts a measurable influence on both the energy and operational parameters of the checkpoint system.

In Figure 2, the cumulative energy consumption (in Wh) is plotted against elapsed time for scenarios in which 0%, 5%, 10%, and 15% of passengers undergo enhanced screening. Although all curves are approximately linear, their slopes increase sharply as the share of enhanced-screening passengers grows in the 15% scenario; the average slope is about 3.3% higher than in the 0% baseline. This discrepancy accumulates to approximately 65 Wh within an hour, which, when extrapolated to a daily cycle and millions of passengers, represents a significant burden on the airport's energy budget.

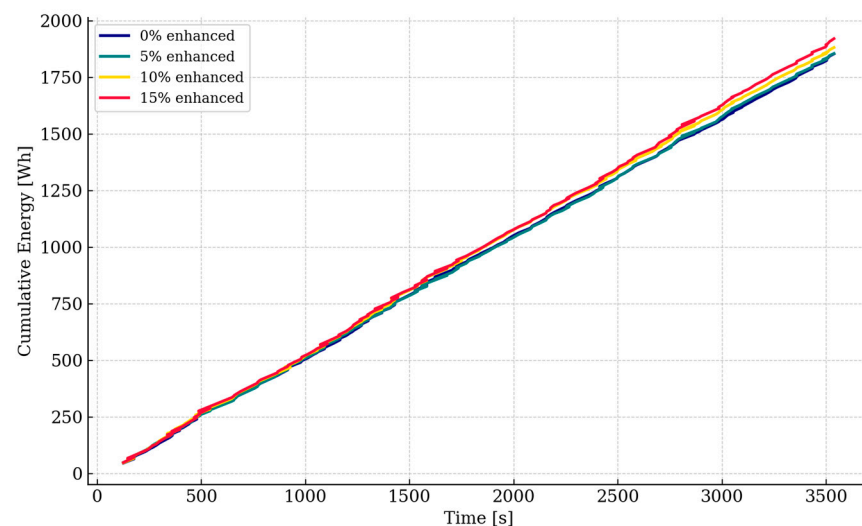


Figure 2. Cumulative energy consumption over time.

Numerical differentiation of the cumulative energy curves yields the instantaneous power profile shown in Figure 3, which reveals brief power spikes exceeding +20 W as well as occasional drops down to −40 W. Both the frequency and amplitude of these transients increase with the percentage of enhanced-screening passengers, indicating more frequent switching of X-ray and ETD devices between standby and active scan modes. Although these transients are short-lived, they may require additional power reserves and can impact the durability of electrical infrastructure.

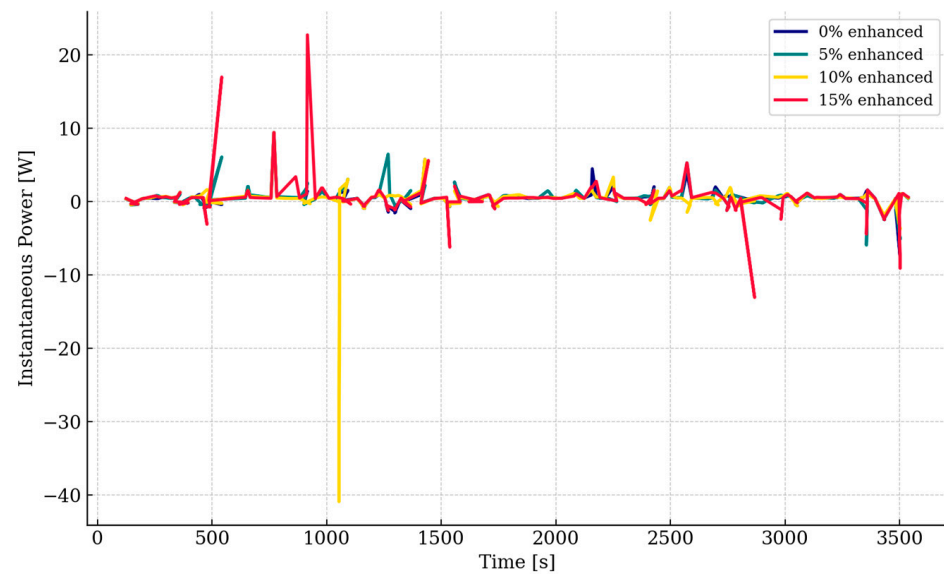


Figure 3. Instantaneous power (dE/dt) profile.

Figure 4 presents the mean power consumption ($\bar{P} = E_{\text{final}}/t_{\text{final}}$) for each scenario, increasing from approximately 0.52 W in the 0% case to roughly 0.54 W in the 15% case. This upward trend confirms a systematic degradation of energy efficiency as procedural load increases.

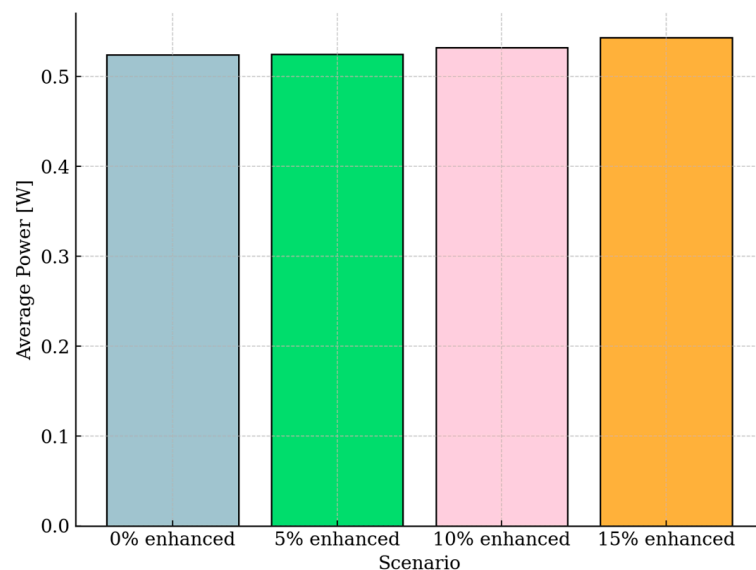


Figure 4. The mean power consumption.

Figure 5 combines the final total energy with the total process duration, showing that a higher share of enhanced screening prolongs the operation time by approximately 0.6% and increases energy usage by more than 4%. This clearly illustrates a trade-off between security level, energy efficiency, and throughput capacity.

The distribution of cumulative energy values within each scenario, depicted as a boxplot in Figure 6, shows the median rising from approximately 940 Wh to about 970 Wh, alongside an increase in the interquartile range and the number of outliers under higher enhanced-screening shares, thus confirming growing variability.

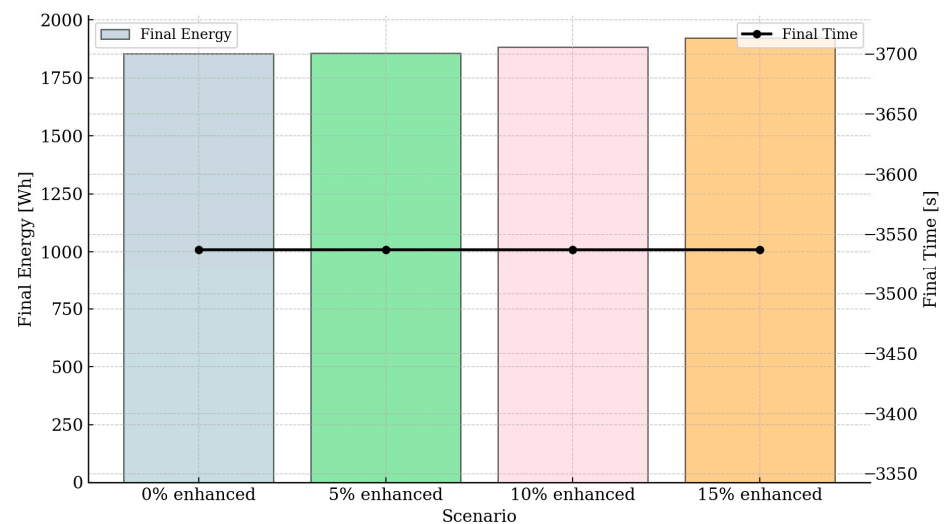


Figure 5. Combining the final total energy with the total process duration.

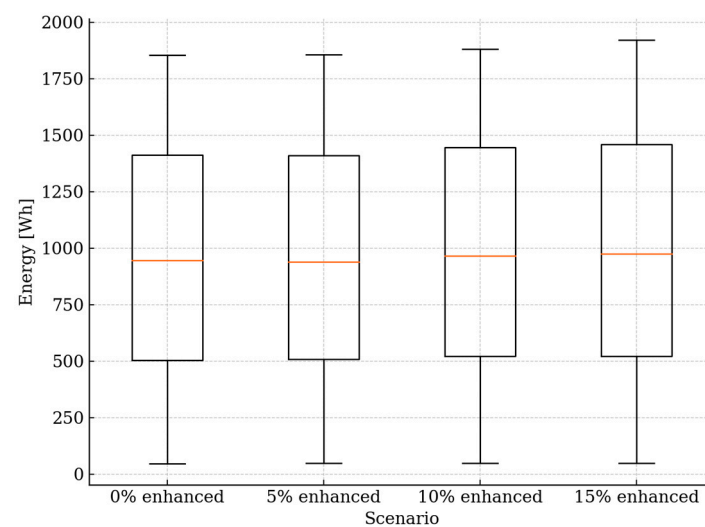


Figure 6. The distribution of cumulative energy values.

Figure 7 shows that the distribution of instantaneous power becomes broader and more asymmetric in scenarios with deeper control.

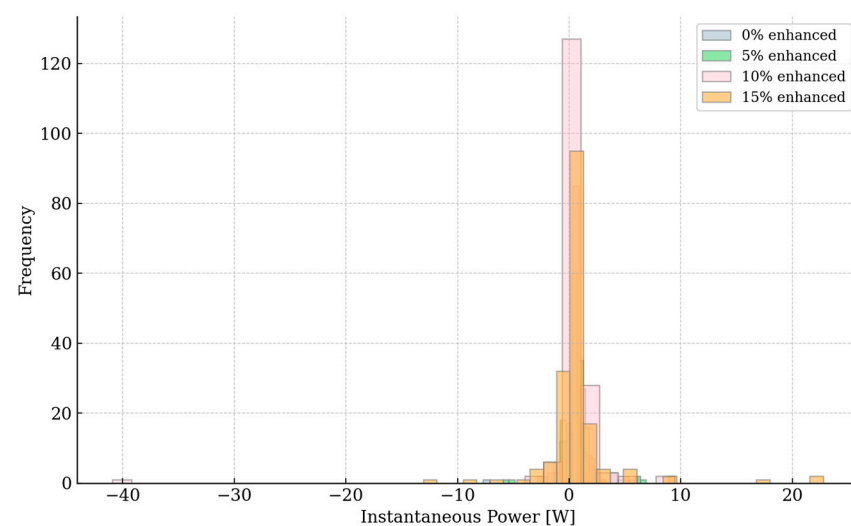


Figure 7. The distribution of instantaneous power.

The analysis results provide several concrete recommendations for airport management. First, the scheduling of emergency power supplies and reserve capacity must account for the abrupt load surges observed in Figures 3 and 7, which occur when screening devices transition between standby and active scanning modes. Second, the formulation of energy budgets and tariff structures should be based on the systematically increasing average power draw (Figure 4) as well as on the total energy consumption and extended system run-time (Figure 5).

The next step, following the descriptive statistical analysis of energy consumption in the airport security control system, was to focus efforts on analysing the energy intensity of the passenger screening process. To this end, an ANOVA was conducted. The statistical analysis began with verification of a key ANOVA assumption, namely the homogeneity of variances among the compared groups. Levene’s test was applied for this purpose, with a result ($p = 0.99$) indicating no significant differences between group variances. This means the assumption of variance homogeneity was met, and there were no obstacles to applying classical ANOVA and post-hoc Tukey HSD tests, even with unequal group sizes.

Subsequently, a one-way analysis of variance was carried out for four independent groups, each representing a consecutive operational scenario. The ANOVA results revealed highly statistically significant differences between groups ($F(3, 656) = 154.11$; $p < 0.0001$). The effect size (eta squared, $\eta^2 = 0.41$) suggests that the factor under study (increasing cultural diversity of passengers in each scenario) accounts for as much as 41% of the observed variance in energy consumption. This effect confirms the very significant impact of the implemented operational changes on energy efficiency.

The next step involved Tukey post-hoc tests, which, by accounting for unequal sample sizes and maintaining error control, enable reliable pairwise comparisons between groups. The results of these tests demonstrated that all scenario pairs differed significantly from each other ($p < 0.001$), confirming a systematic and predictable increase in energy consumption as more advanced operational procedures were introduced.

The table of descriptive statistics (Table 2) reveals a clear, gradual upward trend in average energy consumption across consecutive scenarios. In the “0% enhanced” scenario, the mean energy consumption per pax was 11.66 Wh ($N = 171$); in “5% enhanced”—13.37 Wh ($N = 171$); in “10% enhanced”—14.97 Wh ($N = 164$); and in “15% enhanced”—16.96 Wh ($N = 154$). Comparing these research results with those presented in [17,66], the energy consumption per person in this case is even 30% higher. These differences are not only statistically significant (all pairwise comparisons in Tukey’s post-hoc tests: $p < 0.001$) but also practically meaningful, as there is a consistent, linear increase in energy consumption with the implementation of more advanced scenarios.

Table 2. Results of ANOVA.

Scenario	Mean per Pax [Wh]	Std	Count	95% CI Lower	95% CI Upper
0% enhanced	11.66	2.21	171	11.32	11.99
5% enhanced	13.37	2.30	171	13.04	13.71
10% enhanced	14.97	2.31	164	14.60	15.32
15% enhanced	16.96	2.45	154	16.57	17.34

It is important to note that the lower sample sizes in scenarios 3 and 4 (“10% enhanced” and “15% enhanced”) resulted from the need to implement expanded control procedures for both baggage and passengers, which is typical for real operational conditions and reflects the influence of process complexity on data acquisition capability.

The visualisation of the data in the form of a boxplot (Figure 8) and the distribution of individual measurements provides a better understanding of both central tendencies and variability, as well as the presence of outliers in the analysed scenarios. In each successive scenario, there is an apparent, systematic increase in both the median and average energy consumption. At the same time, the width of the boxes and the length of the whiskers remain stable. This indicates that the implemented changes did not generate uncontrolled fluctuations and that processes remained predictable and well managed, even as procedures became more complex.

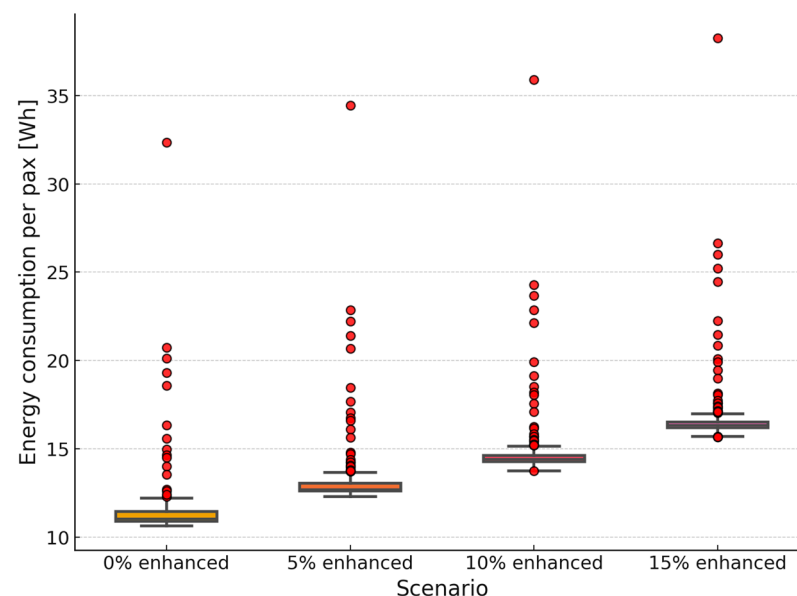


Figure 8. Graphical interpretation of ANOVA test—energy consumption per pax.

The increased values of the standard deviation observed in the analysed scenarios, as well as the presence of outliers on the graph, are a direct reflection of the complexity and variability of security control processes in real conditions. The method of checking passengers and their baggage is characterised by significant operational diversification, resulting from both different behaviours and the varying number of bags carried by individual travellers, as well as from individual cases that require a more detailed or time-consuming procedure (e.g., random checks, system alarms, non-standard baggage, and additional security activities). As a result, even within a single scenario, individual energy consumption measurements can significantly deviate from the average, resulting in increased data dispersion and the emergence of extreme values.

Outliers, visible as individual observations that exceed the typical range of values, are therefore a natural consequence not only of the process's specificity but also of the large number of samples and the broad spectrum of cases covered by the analysis. Their presence does not indicate measurement errors or irregularities in data collection. Still, it reflects real operational variability and sporadic occurrence of non-standard situations, which cannot be eliminated in field studies. Both the value of standard deviation and outliers should therefore be treated as a valuable source of information about the authentic course of the process, and not as elements distorting the interpretation of results.

A natural complement to the ANOVA results was to perform a multinomial regression analysis. This method was chosen for several key methodological reasons. ANOVA only allows for comparisons of means between discrete groups ("0%," "5%," "10%," "15%"), not considering the full continuum of the independent variable. Polynomial regression treats the enhancement percentage as a continuous variable, allowing for modelling and assessing the shape of the relationship curve (linear and weakly nonlinear) and examining possible thresh-

old effects or saturation at higher levels. Furthermore, regression provides direct parameter estimates (trend slope and acceleration) and measures of model fit (R^2), which significantly deepen the conclusions drawn from the ANOVA itself and allow for quantification of the “energy cost” of each additional percentage point. Residual diagnostics (residual plots, Q-Q plot) also allow us to verify key model assumptions (normality, homoscedasticity), which is more difficult to perform precisely in the context of ANOVA.

Finally, regression analysis opens the door to scenario simulations and energy consumption forecasting for any parameter setting, providing a valuable tool for airport managers.

The detailed results of the polynomial regression analysis are presented in Table 3 and Figure 9.

Table 3. Results of the polynomial regression analysis.

Term	Coefficient	Std. Error	<i>t</i> -Value	<i>p</i> -Value	R^2
Model: $y = 11.375 + 0.370x - 0.001x^2$					
intercept	11.375	0.030	379.17	<0.001	0.985
<i>x</i>	0.370	0.011	33.27	<0.001	
x^2	0.001	0.0002	−5.00	<0.001	

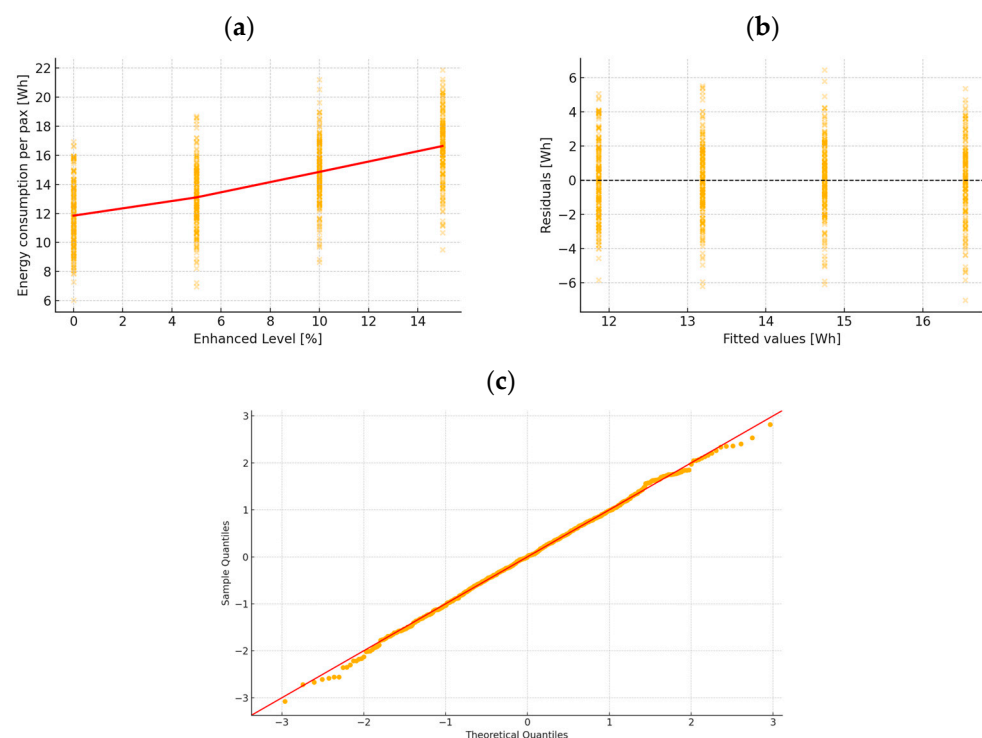


Figure 9. Results of the polynomial regression analysis: (a) Scatterplot with LOESS; (b) Residuals vs. fitted; (c) Normal Q-Q plot.

Figure 9a shows a clear, nearly linear relationship between the percentage of passengers directed to enhanced screening (“Enhanced Level [%]”) and average energy consumption. Initial local smoothing highlights that energy consumption systematically increases with increasing screening levels, with a slight flattening observed at the highest points, consistent with the quadratic term included in the model.

An analysis of the residuals as a function of the fitted values (Figure 9b) reveals their uniform dispersion around the zero line, with no discernible pattern of dependence on the consumption level predicted by the model. The lack of increasing width of the residual

dispersion with the fitted value demonstrates that the assumption of homoscedasticity is met, and the variances of the residuals are stable throughout the prediction interval.

Figure 9c also confirms that the residuals approximate a normal distribution—the points are aligned close to the reference line, with occasional, mild deviations at the extremes, indicating acceptable levels of skewness and kurtosis. This allows us to conclude that the quadratic regression model meets key assumptions regarding the distribution and variance of errors, ensuring the reliability of parameter estimates and the validity of forecasts.

The fitted polynomial model, including both linear and quadratic components, explains 98.5% of the variance in energy consumption ($R^2 = 0.985$). The obtained results show that increasing the share of culturally diverse passengers initially increases energy expenditure almost linearly, while at the highest levels, the deviation from linearity is minimal. Practically speaking, this means that each additional 1% of passengers directed to enhanced screening increases average energy consumption by approximately 0.37 Wh per person. The slow increase at 15% suggests a mild infrastructure saturation effect, typical of a sudden increase in load.

A high R^2 value ensures that the proposed model explains almost all the variability in energy consumption, which has significant practical implications. It allows for the prediction of operational impacts and the optimisation of procedural scheduling in a predictable and controllable manner. Therefore, combining ANOVA with polynomial regression creates a coherent, multivariate analytical framework that provides both evidence of the significance of differences and tools for their quantitative description and prediction.

This stability and predictability of results are of significant value from the perspective of organisational management. The literature on diversity management and cultural competencies [67–69] emphasises that the implementation of DEI policies and cross-cultural training is not directly associated with an increase in energy consumption, but may indirectly support process stability by improving collaboration, communication, and operational efficiency. Thus, the gradual, predictable increase in energy consumption observed in this analysis may be interpreted as evidence of the effectiveness of the implemented procedures and the organisation's ability to control energy costs while achieving qualitative objectives.

When analysing the results from a cost–benefit perspective, it is worth noting that a moderate increase in energy consumption should not be regarded as an obstacle, but rather as a predictable cost accompanying the pursuit of other valuable objectives, such as improved service quality, security, or team cooperation efficiency.

In interpreting the results, it is necessary to consider the limitations of the analysis. Firstly, the group sizes were unequal, which could affect the precision of variance estimation. However, Levene's test confirmed homogeneity of variances, and the large number of observations in each group increases the credibility of the results. Secondly, the study did not analyse the direct impact of specific DEI actions or other organisational factors on energy consumption—the conclusions pertain more to the general predictability of the process.

A further limitation of this study is that, from a management perspective, the cost–benefit analysis should consider not only the measurable increase in energy consumption resulting from the implementation of more advanced scenarios, but also the potential long-term organisational benefits that may arise from improved collaboration, higher service quality, or more efficient management. The observed moderate increase in energy consumption should therefore be viewed not as an obstacle, but as a predictable cost associated with achieving other valuable objectives.

Research has shown that, in parallel with energy planning, throughput optimisation at security checkpoints should utilise adaptive lane allocation algorithms and dedicated processing lanes for passengers requiring enhanced screening. Equally critical are training programs that develop the intercultural communication skills of staff, thereby minimising

the need for additional interventions and reducing the number of re-scans. This approach, in turn, mitigates the negative impact on throughput and improves the overall energy efficiency of the system. By considering the relationship between passenger cultural profiles and energy consumption characteristics, it becomes possible to design a screening process that is both sustainable and reliable, combining the highest standards of protection with optimised operational and environmental costs.

6. Conclusions and Future Work

The analysis of the obtained results indicates that the increasing share of passengers requiring enhanced security screening, primarily associated with cultural diversity and personal differences, constitutes a significant factor influencing both the operational efficiency and cost structure of airport security checkpoints. Considering these findings, the authors recommend that multifaceted managerial and organisational measures be implemented to maintain appropriate system throughput while minimising operational and energy costs.

One of the key directions for intervention should be the flexible scheduling of security checkpoint operations, based on regular analysis of passenger structure and forecasting periods of increased participation of individuals requiring extended procedures. This approach enables the dynamic adjustment of the number of active checkpoints to meet current needs, optimising the use of both human and technical resources. Simultaneously, a crucial element of management strategy is the development and implementation of advanced tools supporting intercultural communication. The application of visual solutions, pictograms, and informational materials in multiple languages, as well as systematic staff training in cultural competencies, contributes to reducing service times and minimising the number of unanticipated interventions.

In terms of efficient resource management, it is essential to implement systems enabling the dynamic allocation of checkpoints and staff based on current operational data. This practice enables rapid adaptation to changing passenger structures, reducing the risk of process bottlenecks. Additionally, where justified by passenger composition and cultural requirements, it may be appropriate to designate dedicated checkpoints for individuals requiring specific procedures, which significantly enhances passenger comfort and limits negative impacts on the overall process flow.

A critical component of systematic improvement is the regular monitoring of operational and energy indicators, including periodic audits of efficiency and energy consumption. This approach facilitates early identification of trends, process optimisation, rational investment decisions, as well as transparent reporting of the effects of implemented measures. Cooperation with airlines—incorporating analytical results into tariff and cost policies and maintaining clear communication regarding the causes and consequences of any service cost increases—promotes transparency and enhances the effectiveness of the entire airport ecosystem.

The impact of these findings on shaping airport environmental policy is significant. The increase in energy consumption associated with the growing number of enhanced screenings, although relatively small in hourly terms, translates into a considerable rise in the airport's carbon footprint over the course of a year and millions of processed passengers. Consequently, in accordance with the guidelines of international organisations such as ICAO and ACI Europe, airport operators should incorporate these results into their decarbonisation strategies and plans for reducing greenhouse gas emissions. Of particular importance is investment in high-energy-efficiency technologies, such as the implementation of modern devices with reduced energy consumption and the modernisation of infrastructure, for example, using LED lighting in control zones.

Parallel to this, raising ecological awareness among personnel is essential, through training in the practical use of equipment, minimising device idle states, and implementing best practices in workstation configuration. Transparent reporting of energy consumption indicators as part of ESG reports represents a crucial aspect of management, enabling benchmarking against other airports internationally and strengthening competitive position. Ultimately, the effective implementation of these recommendations requires close cooperation between airport operators, airlines, technology providers, and supervisory institutions, focused on designing solutions that optimise both operational safety and energy usage.

The authors' future research directions include three trends. In the first case, it is planned to develop detailed forecasting models that consider variables such as cultural background, knowledge of foreign languages, or special needs, to predict system load and optimise resource allocation more accurately. In the case of the second trend, detailed decarbonization strategies will be developed that take these data into consideration. As a third direction for future research, the authors propose building a compromise model that combines four yet often contradictory goals: a high level of passenger safety, optimisation of energy consumption, maintaining an acceptable level of service (LOS), and punctuality of air traffic. Previous works have focused mainly on individual aspects of this system—minimising delays, reducing energy consumption of control devices, improving LOS or strengthening safety procedures. As a result, no integrated approach allows for precise planning of control during peak hours or implementation of dynamic queue management algorithms, thus minimising energy consumption and the risk of delays while maintaining the assumed safety and quality of service standards.

In summary, implementing the conclusions from research will enable airports not only to manage the growing complexity of passenger services more efficiently but also to achieve environmental objectives and build a competitive advantage in the dynamically changing aviation transport sector.

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