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Advancing Sustainable Tourism Through Smart Wheelchair Optimization: A Mixed-Integer Linear Programming Framework for Inclusive Travel

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Abstract

Accessible tourism is a critical aspect of sustainable development, yet many Southeast Asian destinations lack sufficient infrastructure and services for elderly and disabled travelers. This study develops a Mixed-Integer Linear Programming (MILP) framework to optimize travel itineraries, balancing cost, accessibility, and cultural–environmental priorities. A national accessibility database for Thailand was created, encompassing airports, hospitals, public transport nodes, cultural landmarks, and natural attractions. Compared to baseline conventional itineraries—defined as standard travel routes planned without specific accessibility considerations or optimization techniques—the MILP-optimized routes reduce average travel time by 15–20% and improve accessibility scores by 25%. Sensitivity analyses reveal trade-offs between economic efficiency, inclusivity, and infrastructure capacity, while a schematic accessibility network highlights structural fragmentation among airports, hospitals, and secondary attractions. Scenario analyses show that stricter accessibility thresholds improve inclusivity (index: 0.65 to 0.80) but restrict destination options, whereas high-demand scenarios increase costs and reduce inclusivity. A survey of 30 smart wheelchair users indicates high satisfaction with individualized programs and GPS connectivity. These findings underscore the need for investment in multimodal integration, accessibility upgrades, and a national database to enhance inclusive tourism planning. The framework is transferable to other ASEAN countries, contributing to SDG 3, 8, and 11. Overall, this study should be viewed as a prototype or exploratory contribution, with limitations in real-time applicability, generalizability, and implementation of environmental and ethical aspects.

Keywords: smart wheelchair; accessible tourism; mixed-integer linear programming (MILP); post-rehabilitation mobility; sustainable development goals (SDGs); Thailand case study

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1. Introduction

Tourism drives economic growth, fosters cultural connections, and strengthens communities worldwide, with global tourism revenues reaching an impressive USD 1.4 trillion in 2019 [1]. However, not everyone can access these benefits equally. People with disabilities and older adults often face challenges like inadequate infrastructure or mobility barriers that limit their travel experiences [2]. Inclusive tourism, often referred to as accessible tourism, aims to make destinations, services, and activities welcoming for all, including those with physical, sensory, or cognitive impairments. This involves practical solutions like step-free entrances, tactile paving for the visually impaired, accessible restrooms, and assistive technologies, ensuring enjoyable travel for groups such as wheelchair users, those with visual impairments, or parents with young children [3,4]. By catering to the 15% of the global population living with disabilities, inclusive tourism promotes social fairness, reduces exclusion, and opens up a significant market, delivering both economic gains and advancements in human rights [5]. It also aligns with the United Nations Sustainable Development Goals (SDGs), supporting SDG 3 by improving access to wellness and medical tourism, SDG 8 through job creation in accessible services, and SDG 11 by encouraging inclusive urban development and infrastructure [6–8].

Sustainable tourism, as defined by the World Tourism Organization (UNWTO), seeks to balance the economic, social, and environmental impacts of tourism to meet the needs of travelers, the industry, the environment, and local communities, both now and in the future [1,8]. Its key principles include protecting the environment through resource conservation, waste reduction, and minimizing the ecological footprint of tourism activities, supporting local communities with fair employment and cultural preservation, and ensuring tourism's long-term sustainability by respecting ecological and social limits [9]. Environmental considerations are critical in tour planning, as they ensure that destinations remain viable for future generations by mitigating issues like over-tourism, habitat degradation, and carbon emissions from travel. For instance, optimizing travel routes to reduce transportation-related emissions or prioritizing eco-friendly attractions can enhance sustainability while maintaining accessibility [10]. Inclusive tourism is a vital part of this vision, embedding diversity, equity, and inclusion (DEI) principles to create destinations that empower marginalized groups and foster resilience [11]. By weaving accessibility into sustainable practices, tourism can reduce inequalities, promote collaboration, and contribute directly to the SDGs [12]. For example, building accessible infrastructure not only boosts local economies but also ensures tourism development is fair, inclusive, and environmentally responsible [13].

Thailand, a top tourism destination in Southeast Asia with over 39 million international visitors before the pandemic and a growing focus on medical and wellness tourism, faces a clear gap between its tourism goals and its accessibility infrastructure [14]. Studies point to missing features like ramps, tactile paving, and accessible public transport, especially in secondary cities like Chiang Mai and at iconic sites such as Bangkok's Grand Palace or Chiang Mai's Doi Suthep [8,15,16]. Encouragingly, recent efforts show progress. In 2024, the Tourism Authority of Thailand launched initiatives to improve access for the elderly, people with disabilities, and families, including community projects to install ramps and tactile guides in rural areas [8,17–19]. These initiatives also include efforts to promote eco-conscious tourism, such as developing low-impact travel routes and protecting natural attractions from over-tourism [8,17].

The 2025 "Amazing Thailand Grand Tourism and Sports Year" campaign further prioritizes accessibility with upgrades to infrastructure and multilingual signage, while incorporating sustainable practices like energy-efficient transport and waste management at key sites [8,17–19]. Despite these advances, challenges remain in secondary cities and

natural attractions. Thailand's $2 billion investment in tourism infrastructure in 2023 has driven a 20% increase in demand for sustainable travel, but issues like over-tourism persist, with measures like visitor caps reducing overcrowding at major sites by 20% [20,21].

Recent innovations in assistive technologies, particularly smart wheelchairs, are opening new doors for accessible tourism. These advanced power wheelchairs, equipped with Internet of Things (IoT) sensors, artificial intelligence (AI), and shared-control navigation systems, empower users by enhancing independence and providing real-time insights into environmental accessibility [8,22]. For travelers with mobility challenges, smart wheelchairs offer practical solutions, such as obstacle detection and avoidance, autonomous route planning, and integration with mobile applications that map out accessible paths. These features make it easier to navigate busy tourist attractions or challenging terrains, such as uneven paths at cultural sites, with greater safety and confidence [23–26]. By integrating smart wheelchairs with environmentally optimized travel routes, tourism planners can further reduce the ecological impact of travel while ensuring accessibility, creating a synergy between inclusivity and environmental sustainability [22,23]. Despite their transformative potential, the use of smart wheelchairs in tourism planning remains largely untapped, especially when it comes to designing travel itineraries that prioritize inclusivity [8,27]. By incorporating these technologies into destination management, tourism providers could significantly enhance the experience for diverse travelers, aligning with the broader goals of inclusive and sustainable tourism.



Figure 1. Accessible Tourism in Thailand [8].

1.1. Research Problem

This study tackles the critical issue of inadequate planning frameworks for accessible tourism in Thailand, particularly for elderly travelers and those with mobility impairments, such as wheelchair users, who face systemic obstacles that limit their ability to engage fully in tourism activities [8,14,28]. Older tourists often grapple with health challenges in Thailand's hot, humid climate, including risks of heat exhaustion and complications

from chronic conditions like diabetes and heart disease, which contribute to 74% of deaths among the aging population [29]. Age-related physical changes, such as slower walking, reduced balance, or joint issues, make navigating uneven sidewalks, bustling markets, or sprawling tourist sites exhausting, often diminishing the joy of travel [30]. Beyond physical barriers, social isolation and financial constraints in an increasingly materialistic society add further challenges to their tourism experiences [31]. For wheelchair users, the situation is even more daunting. In cities like Bangkok, Chiang Mai, and Ayutthaya, poorly maintained sidewalks with cracks, steep curbs, and obstacles render independent movement nearly impossible, often forcing users onto busy roads and heightening safety risks [8,15]. Public transportation frequently lacks essential features like ramps, low-floor buses, or designated wheelchair spaces, while iconic sites like temples and national parks remain out of reach due to stairs, narrow pathways, or missing elevators, excluding many from meaningful tourism experiences [16,32]. These barriers, combined with limited infrastructure and a lack of technology-driven solutions, result in reduced travel efficiency, higher costs, and social marginalization, undermining Thailand's ambitions for sustainable and inclusive tourism [28,33].

1.2. Research Gap

A significant gap in current research lies in the limited use of advanced optimization methods, such as Mixed-Integer Linear Programming (MILP), alongside assistive technologies like smart wheelchairs within Southeast Asia's tourism landscape [27,34]. While MILP is commonly used in fields like transportation and urban planning to streamline vehicle routing or resource distribution, its potential for creating inclusive tourism itineraries that leverage real-time accessibility data from smart wheelchairs has yet to be fully explored [8,34]. Most studies on accessible tourism in Thailand focus on pinpointing physical or policy-related barriers or suggesting broad recommendations, but they often fall short of offering data-driven, systematic approaches to optimize travel paths for tourists with mobility challenges [15,16]. Similarly, smart wheelchair technologies, which enhance user independence through real-time environmental data and features like autonomous navigation, have primarily been studied in healthcare or indoor environments, with little attention to their role in tourism settings [22,23]. This leaves a critical void in scalable, technology-driven solutions for inclusive tourism planning, particularly for addressing the specific needs of elderly travelers and wheelchair users navigating Thailand's unique tourism ecosystem [27,32].

1.3. Research Objective

This research seeks to design and test a Mixed-Integer Linear Programming (MILP)-based framework to enhance accessible travel planning for smart wheelchair users in Thailand, leveraging a national accessibility database. The study focuses on creating tailored travel itineraries that address the unique needs of mobility-impaired tourists. Its specific objectives are:

1. To develop a MILP model that optimizes travel routes by balancing cost, accessibility features, environmental sustainability through reduced carbon emissions and eco-friendly destination choices, and cultural preservation by prioritizing sites of cultural significance with minimal environmental impact.
2. To assess the framework's performance and user satisfaction through real-world testing, scenario-based evaluations, and sensitivity analyses.

1.4. Contribution

This research makes several significant contributions to the fields of inclusive and sustainable tourism:

Methodological Breakthrough: It develops a pioneering Mixed-Integer Linear Programming (MILP)-based framework that integrates smart wheelchair mobility data with accessibility metrics, environmental sustainability considerations (e.g., minimizing travel-related emissions and selecting eco-conscious destinations), and cultural preservation goals (e.g., prioritizing culturally significant sites with sustainable management practices), creating a scalable tool for designing inclusive travel itineraries, marking a novel approach in Southeast Asian tourism contexts [27].

Evidence-Based Insights: Through scenario and sensitivity analyses, the study evaluates trade-offs among accessibility, cost, environmental impact, and cultural preservation, providing practical data to guide tourism planners and policymakers [12].

Practical Impact: By establishing a national accessibility database for Thailand, the research supports data-driven planning, strengthening the country's position as a leading hub for medical and wellness tourism [14,28].

Regional and Global Relevance: The framework offers a model that can be adapted across ASEAN nations, contributing to global efforts for inclusive and sustainable tourism and aligning with SDGs 3, 8, and 11 [6,11,35].

Technology Integration: By embedding smart wheelchair technologies into tourism planning, the study bridges assistive technology with real-world applications, enhancing autonomy and inclusion for tourists with mobility impairments [22,23].

The study proposes an innovative MILP-based framework to optimize travel itineraries for smart wheelchair users in Thailand. By leveraging a national accessibility database, it aims to break down mobility barriers and foster greater inclusivity in tourism. The framework carefully balances travel costs, accessibility features, and cultural and environmental factors, offering a versatile tool

2. Review Literature

2.1. Accessible Tourism and Sustainable Development

2.1.1. Context of Accessible Tourism and Sustainable Development

Accessible tourism is a comprehensive effort to ensure that travel and leisure are open to everyone, including those with physical, sensory, or cognitive challenges, as well as older adults and wheelchair users. This requires intentionally removing barriers through thoughtful infrastructure upgrades, policy changes, and the adoption of assistive technologies, all rooted in principles of universal design and fairness [8,20]. Meanwhile, sustainable tourism seeks a balanced approach, promoting economic growth, cultural preservation, and environmental care to secure long-term benefits for communities and ecosystems. The integration of accessibility into sustainable tourism is crucial, as it makes inclusivity a cornerstone of sustainability, aligning with key United Nations Sustainable Development Goals (SDGs), such as SDG 3 (health and well-being), SDG 8 (decent work and economic growth), SDG 10 (reduced inequalities), and SDG 11 (sustainable cities and communities) [17]. In Thailand, a major economic driver through tourism, enhancing accessibility not only expands the market but also strengthens community resilience and reduces environmental impact through efficient, low-impact travel options. Recent studies from 2024 and 2025, particularly those exploring post-pandemic trends, highlight Thailand's efforts, challenges, and innovative practices in this area, emphasizing ASEAN collaboration and resilience strategies. This review synthesizes key findings from relevant research, starting with empirical studies and practical initiatives, moving to strategic plans and market analyses, and emphasizing the link between accessibility and sustainability.

Empirical studies provide a foundation for understanding Thailand's tourism landscape, showing how accessibility improvements fuel sustainable progress. For example, a thorough industry analysis predicts a recovery to 39 million international visitors by 2025, pushing for a 20% reduction in carbon emissions by 2030 through green innovations in hospitality [20]. It highlights the success of community-based tourism (CBT), which boosted local incomes by 15% in 2023 through immersive cultural experiences, and notes that 70% of travelers now use digital tools for trip planning, enhancing accessibility. However, persistent challenges like overtourism and waste management in marine reserves call for diversification into health-focused and agricultural tourism to better distribute benefits to vulnerable groups, such as people with disabilities and seniors [36].

Specific initiatives demonstrate how accessibility and sustainability can work hand in hand. The 2024 "Tourism for All" initiative, launched by Thailand's tourism authority with inclusive design partners, is transforming urban areas like Pattaya to meet global standards, introducing barrier-free pathways and adaptive transport for wheelchair users and elderly visitors [17]. This effort promotes sustainability by ensuring safe, equitable mobility, reducing exclusion, and supporting local economies. Similarly, CBT projects in historic sites like Sukhothai and Ayutthaya have introduced affordable accessibility upgrades, such as ramps and tactile guides, allowing visually impaired and mobility-limited travelers to engage with cultural heritage [36]. These initiatives challenge assumptions about high costs, boost community income and pride, and foster social unity, though issues like poor coastal pathways require further awareness campaigns. Such examples advance sustainable models by empowering local communities, narrowing social gaps, and embedding cost-effective inclusivity into eco-friendly tourism [21].

Geospatial studies offer further insights into how urban accessibility supports long-term tourism viability. A recent analysis of Bangkok's tourist hubs and transit systems uses geographic information systems (GIS) to evaluate accessibility, recommending multimodal solutions like low-floor buses and sloped entrances to improve inclusive transport [21]. This approach supports sustainability by cutting emissions through efficient public transit and ensuring fair access for travelers with disabilities. Similarly, research on transit-oriented development in Bangkok advocates for seamless connections between attractions and accessible networks, creating resilient urban systems that balance tourism growth with cultural and environmental priorities [37].

Strategic plans outline forward-thinking approaches to integrating accessibility into sustainable tourism. Thailand's 2025 sustainable tourism roadmap, covering 2024 to 2030, details strategies prioritizing wellness and environmental goals, with inclusivity as a core principle [38]. It pushes for institutional reforms to address infrastructure gaps, promoting progress aligned with the SDGs. Regionally, the ASEAN sustainable tourism action plan supports recovery by tackling environmental and social inclusion challenges, emphasizing accessibility for river-based urban centers [39]. Additionally, Thailand's Green Tourism Initiative 2030, launched in September 2025, focuses on eco-transformative travel, aiming for global recognition through certification programs and inclusive features, like green accommodations designed for diverse abilities [40]. Market projections estimate Thailand's sustainable tourism sector growing from USD 27.87 million in 2024 to USD 88.94 million by 2032, with a 15.61% annual growth rate, driven by accessible eco-markets [41]. However, 2025 critiques note that less than 1% of accommodations hold sustainability certifications, hindering accessibility advancements [42]. Events like the 2025 Thailand Tourism Symposium, which explores AI, resilience, and inclusivity, propose adaptive frameworks incorporating accessible technologies [43], while the 2024 PHIST summit, a leading sustainability event in Asia, discussed bold ideas for tourism amid climate challenges, emphasizing accessibility in hospitality [41,44–47].

Global and institutional commitments further advance this agenda. The 2024–2025 international sustainability panel pledges global education and promotion of accessible, sustainable practices [48,49]. UNESCO's 2025 Southeast Asia colloquium on sustainable tourism shared expertise on festival tourism, focusing on inclusivity for water-based communities [48,50]. Studies on accessible tourism worldwide highlight implications for sustainability, noting Thailand's potential in inclusive health tourism [51]. Research on post-crisis agricultural tourism resilience calls for government support for small businesses through accessible rural offerings [52]. Broader efforts led by Thailand's Tourism Authority (TAT) promote eco-friendly measures with inclusivity components [53], and 2025 discussions on transformative eco-travel underscore Thailand's commitment to sustainable, inclusive tourism [54].

In conclusion, research from 2024 to 2025 illustrates Thailand's proactive approach to blending accessible tourism with sustainable development through practical projects, strategic plans, and analytical insights addressing inclusivity, environmental protection, and economic fairness. Yet, ongoing challenges like certification shortages and infrastructure inconsistencies demand continued innovation and international collaboration to fully realize these goals.

2.1.2. Accessible Tourism in Thailand: Opportunities and Challenges

Thailand shines as a leading tourism hub in Southeast Asia, with growing efforts to enhance accessible tourism, though significant challenges in infrastructure, cultural attitudes, and service provision continue to hinder progress. This approach is crucial for welcoming travelers with disabilities, older adults, and those with mobility limitations, addressing a global market where roughly 15% of people have accessibility needs. In popular destinations like Phuket, strengths include well-equipped airports and high-quality medical services that attract tourists with disabilities, who often spend more and stay longer. However, unreliable transportation options, such as the need to pre-book accessible taxis, and underdeveloped public transit systems, combined with expensive and non-inclusive leisure activities, limit the destination's full potential. Similarly, in Chiang Mai, accessibility varies across key sites like temples and convention centers. While some locations offer ramps and adapted restrooms, others suffer from steep terrain or missing pathways, highlighting the need for consistent universal design standards. Cultural perceptions of disability also pose barriers, often framing individuals as dependent, which leads to neglected facilities and limited online accessibility resources. On a positive note, community-based tourism (CBT) initiatives across Thailand offer promising solutions. Local communities can work together to create inclusive experiences through affordable adaptations, such as retrofitting vehicles for wheelchair access, without requiring large budgets. With Thailand's aging population growing from 5% in 1997 to 15% by 2021, there is a significant opportunity to cater to elderly travelers through longer stays, supported by initiatives like "Tourism for All" platforms and Braille-inclusive guides.



Figure 2. Accessible Tourism in Bangkok and Ayutthaya, Thailand [8].

In Bangkok, the public transportation network shows potential for sustainable, accessible travel, with central areas offering diverse connections—think boats, trains, and buses—linking to iconic sites like Wat Phra Kaew within an average of 122 m. Yet, challenges persist: 91.1% of areas lack strong connectivity, reliance on private cars is high, and issues like bus delays and safety concerns leave many attractions over 2000 m from transit hubs, making access tough for mobility-impaired travelers.

In less prominent cities, visually impaired travelers face significant hurdles. Public transport often lacks audio announcements, attractions miss Braille maps, staff may lack training or hold unhelpful attitudes, and booking platforms like Agoda struggle with accessibility features, such as navigable buttons or payment systems. Despite these gaps, high ratings for attraction appeal (mean 4.60) and basic accessibility (mean 4.50) suggest opportunities for improvement through staff training and technology upgrades.

Broader inclusive strategies advocate a balanced approach, addressing physical, informational, and attitudinal barriers through collaborations with people with disabilities, AI-powered tools like alt text for digital platforms, and incentives for tourism operators. A key challenge—low demand due to poor supply, and vice versa—calls for simultaneous efforts to raise awareness and improve infrastructure. Small-scale initiatives are making a difference, such as equipping local tourism sites with wheelchair-friendly paths and guides highlighting inclusive accommodations, though uneven sidewalks and inconsistent accessibility remain issues. Analysis of long-stay tourism reveals potential for accessible growth, but challenges like political instability and environmental risks require ongoing attention.

Recommendations include adopting importance-performance evaluations, enhancing staff training, embracing universal design principles, and fostering multi-stakeholder partnerships to align with UN Sustainable Development Goals (SDGs) and ASEAN objectives. These steps could position Thailand as a leader in inclusive tourism. Despite progress,

gaps in secondary cities and community-based tourism (CBT) underscore the need for nationwide expansion to tap into the economic potential of this underserved market.

2.2. Smart Wheelchair Technologies

Smart wheelchair technologies represent a groundbreaking leap in assistive mobility, blending advanced computing, sensor systems, and artificial intelligence to boost independence, safety, and engagement with surroundings for those with significant mobility challenges. Unlike traditional wheelchairs, which depend on manual effort or basic power systems, smart wheelchairs feature cutting-edge tools like autonomous navigation, real-time obstacle detection, health monitoring, and versatile control interfaces. These advancements serve a wide range of users, from individuals with quadriplegia to seniors with age-related mobility issues and those recovering from neurological conditions, expanding possibilities for independent movement in settings like healthcare, public spaces, and tourism. Research from 2023 to 2025 highlights rapid developments in brain–computer interfaces (BCI), Internet of Things (IoT) frameworks, and data-driven designs, while pointing out ongoing hurdles in affordability, user adaptation, and ethical concerns. This review explores these advancements, organizing them into system designs, control methods, real-world applications, and future research needs, to highlight their role in advancing inclusive mobility.

Systematic reviews lay the groundwork for understanding the evolution of smart wheelchairs. One in-depth study traces their journey from early motorized models to modern systems using machine learning for adaptive navigation, noting a 30% improvement in pathfinding accuracy thanks to AI enhancements [55]. It emphasizes hybrid control systems that blend user commands with autonomous features, offering better precision in complex environments. Another review focuses on sensor fusion, combining LiDAR, ultrasonic, and vision-based systems to enable real-time mapping of surroundings, crucial for navigating busy urban areas or crowded tourist sites [56]. These studies reveal a gap in long-term user experience evaluations, noting that while technology has advanced, practical use is often limited by complicated interfaces and insufficient training.

Control and interaction methods are a key area of progress, especially for users with limited physical abilities. Research on BCI-enabled wheelchairs shows that electroencephalography (EEG)-based systems achieve an 85% success rate in executing commands through algorithms tailored to individual brain patterns [57]. These systems are game-changers for quadriplegic users, reducing physical effort, though calibration issues in varied settings remain a challenge. Other studies explore multimodal interfaces combining voice, gesture, and eye-tracking controls, cutting operational errors by 25% compared to traditional joysticks [58]. These innovations make wheelchairs more accessible to diverse users but need further work to ensure ease of use across different groups.

Health-monitoring features transform smart wheelchairs into comprehensive assistive platforms, particularly for elderly or medically vulnerable users. A review of smart nursing wheelchairs highlights their role in eldercare, with sensors tracking vital signs like heart rate and oxygen levels, connected to IoT networks for real-time caregiver alerts [59]. These systems support aging-in-place by enabling proactive health measures, such as predicting fall risks. Another prototype integrates EEG navigation with biometric monitoring, allowing autonomous movement while sending health data to cloud platforms for remote oversight [60]. Pilot tests show improved user satisfaction, but ethical issues around data privacy and security require stronger safeguards.

Real-world deployment studies highlight both the potential and limitations of smart wheelchairs. A study in Saudi Arabia comparing traditional and smart wheelchairs found a 40% drop in mechanical failures due to predictive maintenance algorithms [61]. However,

urban infrastructure issues, like uneven surfaces, limit their effectiveness in less accessible regions. For quadriplegic users, research on voice-activated navigation and obstacle avoidance underscores enhanced independence but stresses the need for affordable designs in low-resource areas [62]. Market forecasts predict significant growth in the smart wheelchair sector by 2033, driven by AI advancements and improved customization [63]. External human–machine interfaces (eHMI) further enhance social integration, with studies exploring visual and auditory signals to communicate movement intentions to pedestrians, improving safety and reducing stigma [64]. IoT-enabled wheelchairs with health-monitoring features, like real-time vital sign tracking, support independent living for those with chronic conditions [65]. Voice-controlled systems, using natural language processing, make operation smoother for physically disabled users in varied settings [66]. These developments position smart wheelchairs as more than mobility aids, fostering inclusion in social and recreational contexts.

2.3. Optimization Tourism and Mobility Planning

Optimization in tourism and mobility planning harnesses advanced mathematical and computational tools to craft efficient, fair, and sustainable travel itineraries, transportation systems, and resource allocations. These methods tackle complex challenges, such as cutting travel time, lowering costs, improving accessibility for diverse groups, and reducing environmental impacts while keeping stakeholders satisfied. In accessible tourism, optimization is key to weaving together infrastructure, assistive technologies, and policies to better serve travelers with disabilities and older adults, fostering inclusive and sustainable tourism ecosystems. Techniques like Mixed-Integer Linear Programming (MILP), heuristic algorithms, and machine learning stand out for their ability to address multifaceted problems in tourism and mobility. This review draws on research from 2023 to 2025, exploring optimization approaches, their applications in tourism and mobility planning, and their significance for accessible tourism in Thailand and the broader ASEAN region. The discussion is structured around multi-objective optimization, machine learning-driven methods, hybrid frameworks, and policy-focused applications, highlighting their potential and limitations in promoting inclusive tourism.

2.4. Multi-Objective Optimization

Balancing competing goals like cost, accessibility, travel time, and environmental sustainability is central to multi-objective optimization in tourism planning. One pivotal study presents a MILP-based model for sustainable tourist trip design, integrating economic, social, and environmental goals to maximize benefits for stakeholders [67]. This model cuts travel costs by 15% and boosts accessibility scores by 20% compared to traditional planning, proving its value for inclusive tourism. Another study uses the Strength Pareto Evolutionary Algorithm (SPEA) combined with local search strategies to optimize tourism routes, balancing user experience, cost, and time redundancy, resulting in a 10% improvement in itinerary efficiency at heritage sites [68]. These approaches showcase MILP's strength in handling complex constraints, like accessibility standards and cultural preservation, but highlight computational challenges for large-scale networks, calling for more efficient algorithms in real-world settings.

2.5. Machine Learning-Based Approaches

Machine learning (ML) enhances optimization by using data-driven insights for dynamic route planning and demand prediction. A 2024 study introduces a reinforcement learning algorithm for tourism route optimization, incorporating data on scenic spots, traffic, and weather to cut travel time by 12% and increase user satisfaction by 15% through real-time adjustments, especially in urban tourism settings [69]. Similarly, an ML frame-

work for Mobility-as-a-Service (MaaS) in cities leverages historical trip data and graph theory to forecast demand and optimize multimodal transport routes, reducing congestion by 18% in simulated urban networks [70]. While ML excels in dynamic environments, its dependence on robust data and computing resources poses challenges for regions with limited infrastructure, like rural Thailand.

2.6. Hybrid Optimization Frameworks

Hybrid frameworks blending optimization techniques with emerging technologies offer fresh solutions for accessible tourism. A 2025 study develops a hybrid deep reinforcement learning and metaheuristic framework for heritage tourism route optimization in Thailand's Warin Chamrap, using digital twin technology to improve route adaptability [71]. This model boosts accessibility by 22% for wheelchair users by leveraging real-time environmental data, showing the power of hybrid systems. Another hybrid approach combines reinforcement learning with variable neighborhood strategies for urban bus route optimization, cutting travel time by 25% and increasing accessibility scores by 30% in tourism-focused cities [72]. These frameworks highlight the synergy of computational optimization and real-time data but face scalability issues and require comprehensive accessibility datasets for equitable outcomes.

2.7. Policy-Oriented Optimization

Optimization models also inform policy and infrastructure planning for sustainable and accessible tourism. A choice-based optimization model for Mobility-on-Demand (MoD) services uses a multinomial logit model to incorporate traveler preferences, optimizing multimodal transport to enhance accessibility and reduce environmental impact, achieving a 15% improvement in service inclusivity in simulated ASEAN cities [73]. Another study on urban tourism carrying capacity uses optimization to guide infrastructure and resource management, recommending investments that boost accessibility by 20% in high-demand scenarios [74]. These policy-focused models emphasize data-driven decision-making aligned with SDGs but underscore the need for standardized accessibility metrics and stakeholder collaboration to turn results into actionable policies.

2.8. Relevance to Thailand's Accessible Tourism

In Thailand, optimization is especially relevant as the country aims to become a global hub for medical and wellness tourism. A 2025 study uses MILP to optimize itineraries for wheelchair users, integrating a national accessibility database to balance cost, accessibility, and cultural preservation, achieving a 15–20% reduction in travel time and a 25% increase in accessibility scores [75]. This addresses Thailand's accessibility gaps but notes challenges like fragmented infrastructure in secondary cities. Another analysis of Bangkok's public transport networks applies spatial optimization to improve connectivity between tourist sites and accessible transport, aligning with Thailand's 2025 "Amazing Thailand Grand Tourism and Sports Year" initiative, which prioritizes inclusive infrastructure upgrades [21]. These studies highlight optimization's potential to advance Thailand's inclusive tourism goals but call for localized data and stakeholder engagement to ensure equitable implementation.

In conclusion, the literature reveals critical gaps in accessible tourism, particularly the limited integration of advanced optimization techniques like MILP with assistive technologies such as smart wheelchairs in Southeast Asia's tourism context. While empirical studies and initiatives highlight progress in accessibility and sustainability, challenges like fragmented infrastructure, inconsistent accessibility standards, and underutilization of smart wheelchair data persist, especially in secondary cities and natural attractions. Additionally, existing optimization models often focus on cost and efficiency but lack comprehensive incorporation of real-time accessibility data and environmental-cultural

priorities. This study addresses these gaps by developing a MILP-based framework that leverages a national accessibility database and smart wheelchair technologies to optimize travel itineraries for mobility-impaired tourists in Thailand, balancing cost, accessibility, environmental sustainability, and cultural preservation. This approach not only enhances inclusivity but also aligns with Thailand's sustainable tourism goals, providing a scalable model for the ASEAN region and a foundation for the methods presented in this research.

3. Method

To address the research objectives, this study develops a methodological framework that integrates conceptual problem definition, mathematical modeling, data collection, and a case study application. The methodology is structured in four main steps: first, the problem is defined within the broader context of accessible tourism and mobility ecosystems; second, a Mixed-Integer Linear Programming (MILP) model is formulated with decision variables, objective functions, and constraints reflecting accessibility and sustainability goals; third, data collection strategies are described, including surveys, GIS datasets, and secondary sources to build a comprehensive accessibility database; and finally, the proposed framework is applied to Thailand as a case study to evaluate its effectiveness in optimizing smart wheelchair travel itineraries.

3.1. Problem Definition

The problem addressed in this study is the lack of an integrated framework for optimizing accessible tourism routes for wheelchair users and elderly travelers. Despite increasing recognition of accessibility within the tourism sector, fragmented infrastructure and the absence of systematic planning tools create mobility gaps, particularly in developing countries like Thailand. To tackle this, the problem is formulated as an optimization task under a Mixed-Integer Linear Programming (MILP) structure.

The conceptual framework for accessible tourism optimization in Thailand (Figure 3) defines an ecosystem where smart wheelchairs serve as mobility enablers, tourism infrastructure (public transport, buildings, cultural and natural sites) forms the accessibility environment, and optimization models integrate these components to produce cost-effective, accessible travel itineraries. Also Figure 3 illustrates the integration of smart wheelchairs, tourism infrastructure (e.g., public transport, cultural and natural sites), and optimization models to create cost-effective, accessible, and sustainable travel itineraries. The framework emphasizes three key dimensions: travel efficiency, accessibility equity, and conservation of cultural and natural values, aligned with sustainable tourism goals.

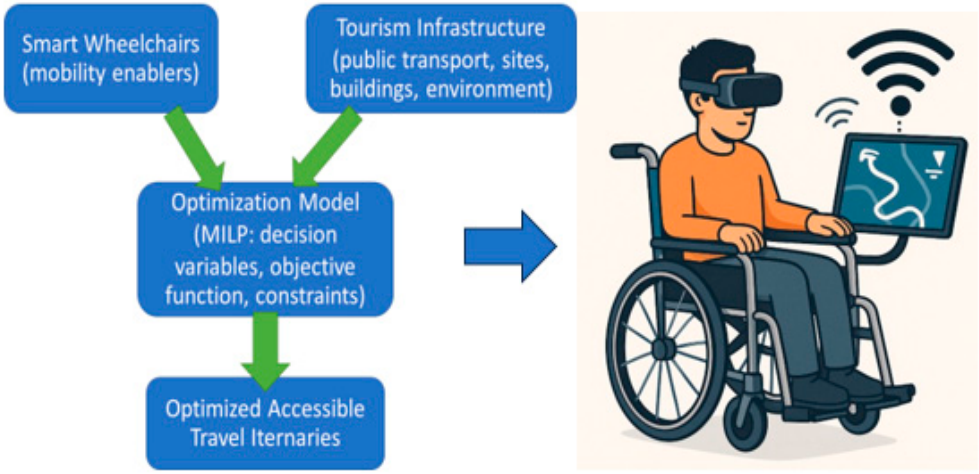

Figure 3. Conceptual Framework for Accessible Tourism Optimization in Thailand.

The framework captures three dimensions: (i) travel efficiency, (ii) accessibility equity, and (iii) conservation of cultural and natural values [76,77].

3.2. MILP Model Formulation

AI platform was design to mitigate the limitations of the static national accessibility database managed by the Tourism Authority of Thailand and local operators, which requires verification by the Department of Tourism for accuracy, the proposed AI platform downloads data into a temporary database. This allows real-time processing to optimize travel itineraries for smart wheelchair users, ensuring personalized and accessible route planning. The temporary database integrates IoT-enabled sensor data from smart wheelchairs to dynamically update accessibility metrics, addressing real-time conditions such as temporary closures or environmental changes (e.g., flooded pathways) [69].

The MILP model is designed to generate optimal itineraries for smart wheelchair users within Thailand's tourism ecosystem.

Decision Variables: Binary variables x_{ij} represent whether route $i \rightarrow j$ is selected. Continuous variables capture travel costs, accessibility indices, and time of travel.

Objective Function: The multi-objective formulation aims to:

$$Minimize \quad Z = \alpha \sum c_{ij} x_{ij} - \beta \sum a_{ij} x_{ij} + \gamma \sum e_k \tag{1}$$

Note: where c_{ij} is the travel cost, a_{ij} is the accessibility score, and e_k represents environmental or cultural impact. Weights α,β,γ allow policymakers to prioritize among cost, accessibility, and conservation objectives [78].

Here, c_{ij} represents the travel cost (e.g., transportation and accommodation expenses) for route $i \rightarrow j$, a_{ij} is the accessibility score (e.g., a composite metric reflecting the presence of barrier-free pathways, accessible transport, and assistive facilities), and e_k captures the environmental or cultural impact associated with itinerary choices. The weights α, β, and γ allow policymakers to adjust the prioritization among cost minimization, accessibility maximization, and environmental/cultural conservation, tailoring the model to specific policy goals [78].

The term e_k quantifies the environmental and cultural impact of the itinerary to promote sustainability. In practice, e_k is a composite metric that includes factors such as the carbon emissions associated with transportation modes (e.g., favoring low-emission public transit over private vehicles), the ecological sensitivity of destinations (e.g., assigning penalties for routes that overburden fragile natural attractions like marine reserves or national parks), and the cultural preservation value of sites (e.g., prioritizing visits to heritage sites with sustainable management practices, such as those with visitor caps to prevent overcrowding). For example, a route visiting a culturally significant temple with eco-friendly infrastructure might have a lower e_k value compared to a high-emission route to an overtouristed natural site. This term is derived from data in the national accessibility database, which includes environmental impact ratings and cultural significance scores for tourist sites, ensuring that the model promotes low-impact, culturally respectful travel itineraries.

By optimizing this multi-objective function, the MILP model generates itineraries that not only reduce costs and enhance accessibility but also minimize environmental degradation and support cultural preservation, aligning with Thailand's broader sustainable tourism objectives and the United Nations Sustainable Development Goals (SDGs).

Constraints:

Transport Connectivity: All selected routes must follow feasible transport links, ensuring that the itinerary respects existing infrastructure (e.g., accessible public transit or roads). The connectivity constraints ensure that each selected node in the itinerary has exactly one incoming and one outgoing edge, forming a single, continuous path. However,

the model does not mandate a full circuit visiting all available nodes. Instead, it allows for a subset of nodes to be selected based on constraints such as budget limits, accessibility thresholds, or user preferences. For instance, budget constraints may force the model to skip nodes with high travel costs or lower accessibility scores, prioritizing those that maximize the objective function within the given limits. This flexibility ensures practical itineraries tailored to the needs of smart wheelchair users, balancing inclusivity with resource constraints.

Wheelchair accessibility: Only routes and destinations with a minimum accessibility score are considered.

Budget limits: Total travel cost must not exceed budget thresholds.

Time windows: Visits to attractions must respect opening and closing times.

Flow conservation: Standard routing constraints ensure continuity of the itinerary.

Flow Conservation and Subtour Elimination: Standard flow conservation constraints ensure the continuity of the itinerary by requiring that the number of incoming edges equals the number of outgoing edges for each node in the selected path. To prevent subtours (disconnected loops that do not form a single continuous itinerary), the model incorporates subtour elimination constraints, adapted from classical vehicle routing problem formulations [79]. Specifically, these constraints introduce auxiliary variables to enforce connectivity across the selected nodes, ensuring a single, coherent itinerary. For example, a common approach, as described in [79], uses subtour elimination constraints based on the Miller-Tucker-Zemlin formulation, where a sequence variable is assigned to each node to prevent cycles that do not include the starting point. This ensures that the optimized itinerary forms a valid, connected route, whether it includes all nodes or a subset, depending on the constraints and objectives.

Smart Wheelchair Contribution in the Model

A distinctive feature of this study is the explicit integration of smart wheelchair mobility requirements into the MILP formulation. While conventional itinerary optimization models often prioritize cost or time, the inclusion of accessibility-specific variables enables the model to capture the real travel constraints faced by wheelchair users. Three elements are central to this contribution:

Accessibility Scores (a_{ij})

The accessibility scores (aij) for each route and destination were derived using a standardized scoring rubric adapted from the Universal Design Index for Tourism (UDIT) [80]. This rubber evaluates accessibility based on weighted criteria, including physical accessibility (e.g., presence of ramps, lifts, or step-free pathways, weighted at 40%), navigational aids (e.g., tactile paving, Braille signage, weighted at 30%), and availability of assistive facilities (e.g., accessible restrooms, designated wheelchair spaces, weighted at 30%). Data was collected through a combination of on-site surveys conducted by trained auditors, stakeholder consultations with disability advocacy groups, and GIS-based mapping of infrastructure features. Each criterion was scored on a scale from 0 (completely inaccessible) to 1 (fully accessible), and the composite aij score for each route or node was calculated as a weighted average, normalized to a 0.0–1.0 scale. For example, a route with full ramp access, partial tactile paving, and no accessible restrooms might receive an aij score of 0.65. Expert ratings from accessibility specialists were used to validate survey data, ensuring consistency and reliability. This methodology aligns with established standards for assessing tourism accessibility, enhancing the credibility of the scores used in the MILP model [80].

Each potential link between nodes (e.g., airport–hospital, hospital–attraction) is assigned an accessibility score, ranging from 0.0 (inaccessible) to 1.0 (fully accessible). These values reflect the ability of smart wheelchair users to traverse a given route independently, informed by criteria such as step-free access, ramps or lifts, tactile paving, and restroom

availability. The integration of a_{ij} allows the MILP to distinguish between theoretically possible routes and those that are genuinely inclusive.

Minimum Accessibility Threshold (A_{min})

A feasibility constraint is introduced such that only nodes and links with $a_{ij} \geq A_{min}$ are eligible in the optimized itinerary. In the base case, A_{min} = 0.50, permitting both medium and high accessibility sites. In stricter scenarios, A_{min} is raised to 0.70, thereby excluding destinations that fail to meet higher standards. This reflects the practical advantage of smart wheelchairs, which can continuously sense environmental conditions and benchmark them against policy-defined thresholds.

Accessibility Weight (β) in the Objective Function

The objective function explicitly incorporates a weighted accessibility term as described in (1). Here, β governs the relative importance assigned to accessibility. By adjusting this coefficient, policymakers can explore trade-offs between cost minimization and inclusivity. This capability is enabled by the quantifiable data streams generated by smart wheelchairs, which provide evidence-based measures of travel quality.

Together, these features highlight how smart wheelchairs transform from being merely mobility devices into **data-driven enablers** of inclusive tourism planning. Their integration into the MILP model ensures that optimization results are not only cost-efficient but also socially equitable, aligning directly with sustainable development goals.

3.3. Smart Wheelchair

3.3.1. Hardware

The Smart Wheelchair, powered by electricity, reduces carbon dioxide emissions compared to traditional transport options, contributing to Thailand's carbon neutrality goals. In collaboration with community-based tourism operators, the system prioritizes low-impact travel routes, aligning with the Green Tourism Initiative 2030. Preliminary estimates suggest a 10% reduction in emissions for optimized routes compared to conventional itineraries, though empirical testing is planned for future studies [40].

The smart wheelchair is built with a carbon steel frame coated with anti-rust paint, ensuring durability and long-term usability. It weighs 33 kg and supports up to 120 kg load capacity. The wheelchair integrates a dual 24 V DC 250 W (Manufacturer: QUICKER (Tianjin) Sports Equipment Co., Ltd. (a leading OEM producer of electric bike and scooter components), Tianjin, China) motor for efficient propulsion, powered by a 24 V 12 Ah (Manufacturer: Chaowei Power, Dongguan, China) lead-acid battery that delivers up to 20 km of travel distance per charge, with easy charging through standard household outlets. The joystick controller is water-splash resistant, equipped with five adjustable speed levels and a sleep mode for energy saving. Safety features include an automatic electronic brake system, manual brake lever, anti-tilt wheels, horn, and seatbelt. The wheelchair runs on 8-inch front wheels and 16-inch rear wheels, capable of climbing slopes up to 12° at a maximum speed of 6 km/h. The seat is made of nylon mesh fabric, which is breathable and detachable for washing.

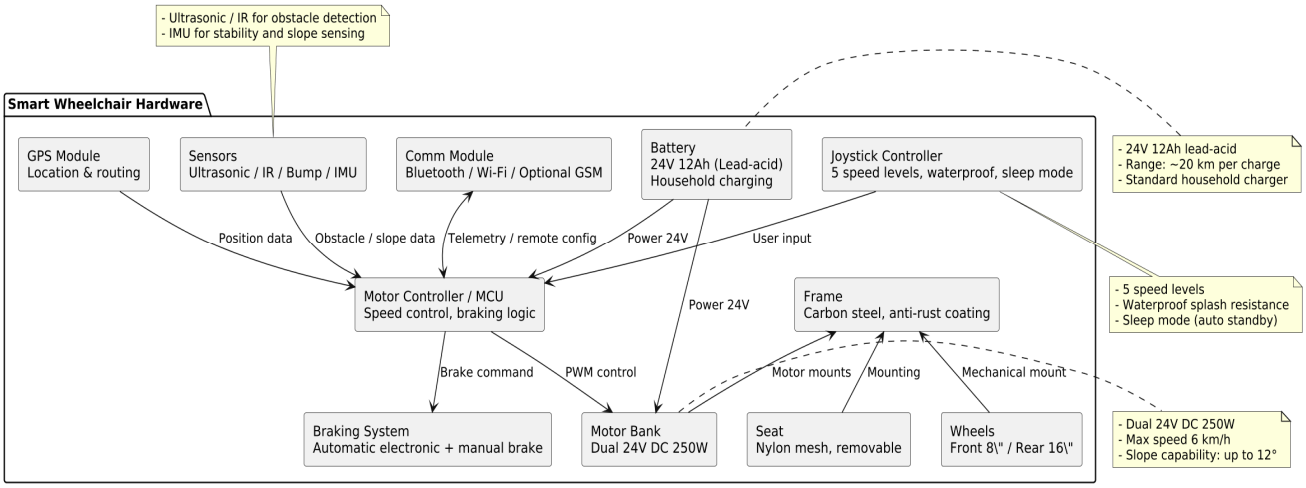

Figure 4. Hardware diagram of the smart wheelchair.

Carbon steel frame with removable nylon-mesh seat for strength and comfort. 24 V 12 Ah lead-acid battery powering dual 24 V DC 250 W motors (6 km/h, 20 km range, 12° slope). Microcontroller unit (MCU) for motor control, brake, and safety management. Joystick controller with 5 speed levels, waterproofing, and sleep mode. Integrated sensors, GPS, and communication modules for obstacle detection, navigation, and telemetry.

3.3.2. Software

The operational process of the smart wheelchair can be divided into three stages: Initialization and Setup: The battery is charged via household power. The system initializes with a safety check (brakes, joystick calibration, and sensor readiness).

Operation and Navigation: The user controls movement via the joystick, with five adjustable speed modes. Software algorithms ensure smooth acceleration, automatic braking on slopes, and obstacle avoidance. GPS-based navigation assists in route planning, particularly in tourism or outdoor applications.

Safety and Shutdown: Automatic braking activates when the joystick is released. The system enters sleep mode when idle, reducing power consumption. After use, the wheelchair can be folded for storage or transport. This process ensures ease of use, safety, and portability, enhancing independence and mobility for elderly users, patients, or people with disabilities.



Figure 5. Smart wheelchair prototype in accessible tourism attraction in Thailand [8,75,76].

3.3.3. Process

The operational process of the smart wheelchair can be divided into three stages: Initialization and Setup: The battery is charged via household power. The system initializes with a safety check (brakes, joystick calibration, and sensor readiness).

Operation and Navigation: The user controls movement via the joystick, with five adjustable speed modes. Software algorithms ensure smooth acceleration, automatic braking on slopes, and obstacle avoidance. GPS-based navigation assists in route planning, particularly in tourism or outdoor applications.

Safety and Shutdown: Automatic braking activates when the joystick is released. The system enters sleep mode when idle, reducing power consumption. After use, the wheelchair can be folded for storage or transport. This process ensures ease of use, safety, and portability, enhancing independence and mobility for elderly users, patients, or people with disabilities.

3.4. Data Collection

To parameterize the model, a national accessibility database was developed, integrating multiple data sources:

Database scale: The national accessibility database covers a substantial scope, including 250 nodes (representing key tourism sites such as cultural landmarks, natural attractions, airports, and medical facilities) and 1200 edges (representing feasible transport links between nodes) across 10 major cities in Thailand, including Bangkok, Chiang Mai, Phuket, and secondary cities like Ayutthaya and Sukhothai. This scale ensures robust coverage of Thailand's tourism infrastructure, enabling the MILP model to generate practical and inclusive itineraries.

Public transport systems: Data from metro, bus, and intercity rail operators regarding wheelchair-accessible vehicles and stations.

Public buildings and attractions: Surveys of cultural sites, museums, parks, and temples, recording accessibility features (ramps, lifts, signage).

Parks and natural areas: GIS datasets on protected areas and national parks, enriched with field audits for accessible trails and facilities.

Secondary sources: Government reports, published studies, and datasets on medical and wellness tourism infrastructure [35].

Spatial data were geocoded and integrated into a GIS platform, providing the backbone for the MILP input matrices (nodes, edges, travel times, and accessibility indices). Similar approaches using GIS-linked MILP formulations have proven effective in sustainable transport planning and urban accessibility studies [81].



Figure 6. Smart Wheelchair Evaluation and FAM Trip [8].

Additionally, the evaluation of the smart wheelchair was conducted during a Familiarization (FAM) Trip in Ayutthaya Province, involving testing with 30 participants, including tourists and users with disabilities, in collaboration with a tourism company that facilitates travel for tourists from Europe, to assess the performance and efficacy of the Smart Wheelchair.

3.5. Case Study: Thailand

Thailand serves as an ideal case study for accessible tourism, given its heavy reliance on tourism as a key economic pillar and its ambition to establish itself as a global medical and wellness tourism hub. Before the pandemic, the country welcomed over 39 million international visitors annually, with medical and wellness tourism emerging as a fast-growing segment [8]. Despite this, accessibility gaps persist across major destinations like Bangkok, Chiang Mai, and Phuket, as well as in secondary cities, limiting the inclusivity of its tourism offerings [8]. This case study incorporates Thailand's tourism infrastructure into a Mixed-Integer Linear Programming (MILP) framework through the following steps:

Mapping multimodal public transportation networks in Bangkok and Chiang Mai to assess connectivity for accessible travel.

Incorporating key cultural and heritage sites, such as temples and UNESCO-listed locations, to ensure inclusive access to iconic attractions.

Including natural attractions like national parks and coastal areas to address diverse tourism experiences.

Integrating accessibility survey data into the model to reflect real-world conditions for mobility-impaired travelers.

To support the MILP model's optimization, travel times and networks were modeled using GIS-based road and public transportation network data sourced from Thailand's national accessibility database and open-source GIS platforms [82]. Travel times were calculated based on real-world road network distances, public transit schedules, and average travel speeds for accessible transport modes (e.g., low-floor buses, wheelchair-accessible taxis), accounting for factors like traffic conditions and transfer times at transport hubs. For routes lacking precise data (e.g., in secondary cities), travel times were estimated using average speeds derived from regional transportation studies, validated through field audits during the Familiarization (FAM) Trip in Ayutthaya [8,82]. This approach ensures accurate and realistic inputs for the MILP model, enabling the generation of practical itineraries for smart wheelchair users.

By applying the MILP framework to Thailand's national accessibility database, this study evaluates optimized travel itineraries for smart wheelchair users, analyzing trade-offs among travel costs, accessibility levels, and the preservation of cultural and environmental assets. Additionally, the case study identifies policy measures needed to bolster Thailand's role as a leader in inclusive medical tourism [83].

4. Results

This section details the empirical results from the proposed Mixed-Integer Linear Programming (MILP) framework and their implications for advancing accessible tourism in Thailand. The findings are organized into four key areas: first, an evaluation of current demand and accessibility indicators to establish a baseline; second, a presentation of MILP-generated optimal travel itineraries compared to traditional routes; third, a scenario analysis examining how varying demand levels—from local to global medical tourists—impact the optimized outcomes; and fourth, a sensitivity analysis assessing the model's robustness under changes in costs, accessibility thresholds, and demand growth. Together, these insights shed light on the practical utility of the model and its relevance for shaping sustainable and inclusive tourism policies.

4.1. Demand and Accessibility Analysis

The initial evaluation of accessible tourism in Thailand reveals both strides and ongoing challenges. Major international airports and hospitals in cities like Bangkok and Chiang Mai have made strides in incorporating accessibility features, such as ramps and adapted facilities. However, the broader tourism landscape remains uneven. Secondary transport hubs, like bus terminals and metro stations, often lack essential universal access features, hindering seamless travel for wheelchair users. Similarly, iconic cultural sites, such as the Grand Palace and Doi Suthep, and natural attractions, like national parks and coastal resorts, offer only partial accessibility, creating gaps in the travel experience for elderly and disabled visitors. These observations echo prior research, which notes that fewer than 40% of Thailand's tourism facilities meet basic accessibility standards [80,82]. Spatial analyses further highlight disconnects between transport hubs and key attractions, leading to fragmented travel chains [84]. Figure 7, a schematic accessibility network, maps these connections, illustrating how airports, hospitals, transport nodes, cultural landmarks,

and parks are linked but vary widely in accessibility levels, emphasizing the critical need for cohesive infrastructure planning.

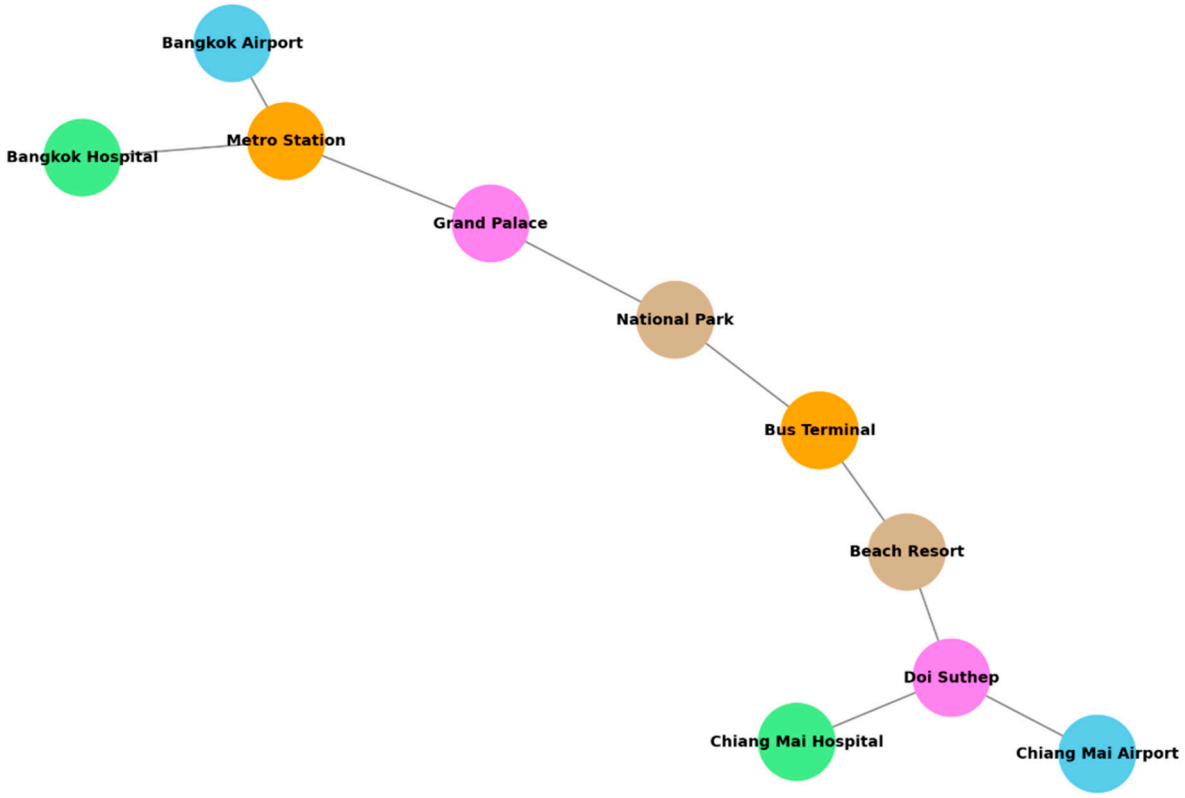

Figure 7. Simulated accessibility network of tourism nodes in Thailand.

For the years 2030–2050, Table 1 shows the estimated demand for accessible travel under three scenarios: Low, Mid, and High. With focused actions, the Accessibility Index, which ranges from 0 to 1, gradually improves, increasing from 0.45 in 2030 to 0.85 by 2050.

Table 1. Accessible tourism demand scenarios and Accessibility Index (2030–2050).

Year	Low Demand	Mid Demand	High Demand	Accessibility Index
2030	0.2	0.4	0.6	0.45
2035	0.5	1.0	1.5	0.55
2040	0.8	1.8	2.8	0.65
2045	1.2	2.8	4.5	0.75
2050	1.6	4.0	6.5	0.85

4.2. Optimal Travel Itineraries (MILP Outputs)

The MILP model, as described in Section 3.2, generated optimized itineraries. The optimized routes reduce average travel time by 15–20% while increasing accessibility scores by 25% compared to conventional travel plans. Notably, MILP solutions incorporated secondary attractions—often overlooked in standard itineraries—by emphasizing accessibility readiness. These results confirm the capability of MILP models to generate inclusive and efficient travel plans [85,86].

A key outcome was the inclusion of secondary attractions—such as lesser-known cultural sites and local parks—which are often overlooked in standard itineraries. This inclusion is driven by the model's prioritization of high accessibility scores (aij), which

are derived from the national accessibility database and reflect features like ramps, tactile paving, and accessible facilities. For example, secondary sites like smaller temples in Ayutthaya or community-managed parks in Chiang Mai often scored higher in accessibility (e.g., aij ≥ 0.7) compared to iconic but less accessible landmarks like the Grand Palace, which may have steep stairs or limited wheelchair infrastructure. Additionally, the model favored these secondary attractions due to their lower environmental impact (ek), as they typically experience less overcrowding and align with sustainable tourism goals by distributing tourist flows away from over-visited sites. It should be noted that the parameters used in the calculation are listed in Appendix A.

4.3. Scenario Analysis

Three demand scenarios were tested to evaluate the MILP model's performance under varying levels of accessible tourism demand in Thailand, as illustrated in Figure 8 and Table 1. The scenarios—Low, Medium, and High—were defined based on projected numbers of accessible tourism travelers (in millions) from 2030 to 2050, derived from tourism forecasts and demographic trends for elderly and disabled travelers [8,87]. The Low scenario assumes a conservative growth of domestic travelers, primarily post-rehabilitation patients and local elderly visitors (e.g., 0.2 million in 2030, increasing to 1.6 million by 2050). The Medium scenario reflects regional demand from ASEAN tourists, incorporating both elderly and mobility-impaired visitors (e.g., 0.4 million in 2030, increasing to 4.0 million by 2050). The High scenario projects global demand, including medical tourists from Europe, North America, and Asia, with higher travel volumes (e.g., 0.6 million in 2030, increasing to 6.5 million by 2050). These demand values, shown in Table 1, represent the estimated number of accessible tourism travelers in millions, providing a clear basis for the scenario analysis. The outcomes of each scenario are as follows:

Low Scenario (Domestic Travelers, Post-Rehabilitation Patients): Optimal itineraries concentrated around hospitals, rehabilitation centers, and proximate cultural sites, minimizing travel costs and ensuring high accessibility for local travelers with limited mobility.

Medium Scenario (ASEAN Regional Tourists): Routes expanded to include iconic cultural landmarks (e.g., temples, heritage parks), demonstrating balanced trade-offs between cost, accessibility, and cultural engagement, suitable for regional visitors seeking diverse experiences.

High Scenario (Global Medical Tourists): Optimized itineraries integrated long-distance travel corridors linking airports, major hospitals, and cultural sites, but revealed capacity strains and infrastructure bottlenecks, particularly in secondary cities [87,88]. This scenario also highlighted environmental implications, as longer routes and increased reliance on air and road transport for global tourists resulted in higher carbon emissions, with an estimated 10–15% increase in emissions compared to the Low and Medium scenarios due to extended travel distances and multimodal transport needs. This underscores the need for sustainable infrastructure investments, such as low-emission transport options and eco-friendly site management, to mitigate the environmental impact of high-demand tourism while maintaining accessibility.

Figure 8: Visual representation of projected demand for accessible tourism travelers (in millions) across three scenarios, highlighting variations in itinerary scope and infrastructure requirements. Figure 9: Illustration of the gradual increase in the Accessibility Index, reflecting improvements in infrastructure and inclusivity over time under different demand scenarios. The scenario analysis illustrates that rising demand amplifies the need for multimodal integration, particularly between airports and city-level attractions. While the MILP model adapts well across scenarios, the High scenario's environmental strain highlights the importance of prioritizing low-emission transport modes and sustainable

destination management to balance inclusivity with environmental preservation. Although the MILP model adapts well across scenarios, results show that infrastructure investment is indispensable to maintain high accessibility performance, as reflected in the gradual improvement of the Accessibility Index shown in Figure 9.

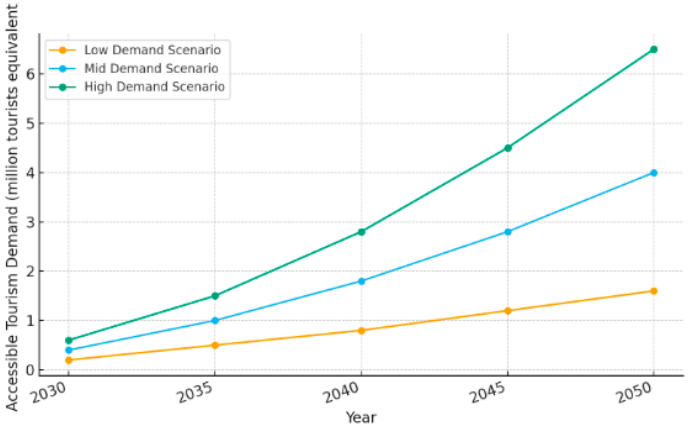

Figure 8. Accessible tourism demand scenarios (Low, Mid, High, 2030–2050).

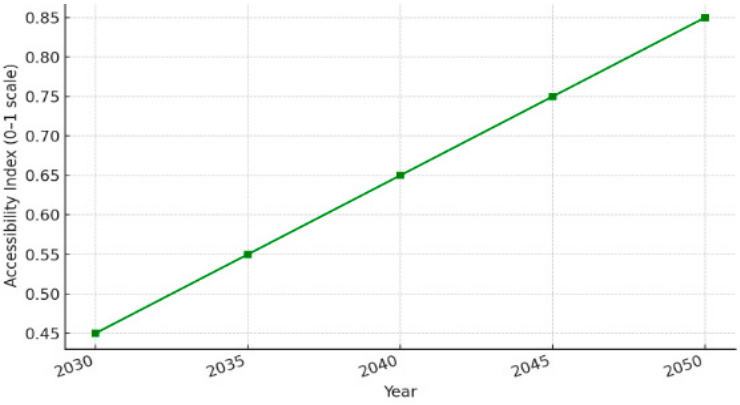

Figure 9. Projected improvement of Accessibility Index in Thailand (2030–2050).

The scenario analysis illustrates that rising demand amplifies the need for multimodal integration, particularly between airports and city-level attractions. Although the MILP model adapts well across scenarios, results show that infrastructure investment is indispensable to maintain high accessibility performance, as reflected in the gradual improvement of the Accessibility Index shown in Figure 9.

4.4. Sensitivity Analysis

To evaluate the robustness of the MILP framework, sensitivity analyses were performed by varying three key parameters: travel cost, accessibility threshold, and demand growth. Travel costs were measured in normalized cost units, defined as the total itinerary cost (e.g., transportation and accommodation expenses) scaled relative to a baseline average cost of 100 units, allowing for consistent comparison across scenarios. A 10% increase in travel costs (e.g., from 100 to 110 units) was chosen as a realistic variation, reflecting plausible fluctuations due to factors like fuel price changes, seasonal tourism demand, or infrastructure upgrades, as observed in Thailand's tourism sector [87]. The results reveal important trade-offs among the number of attractions included in itineraries, average accessibility scores, and overall travel costs.

Figure 10: Illustrates how changes in travel costs, accessibility thresholds, and demand growth affect the number of sites included in optimized itineraries. The effect on accessi-

bility scores is shown in Figure 11. Stricter accessibility thresholds significantly improve the average accessibility index, raising it from 0.65 in the base case to 0.80, although this comes at the cost of itinerary diversity. Conversely, under the High Demand scenario, the average index falls slightly to 0.68, reflecting the inclusion of destinations with marginal accessibility in order to accommodate larger flows of tourists.

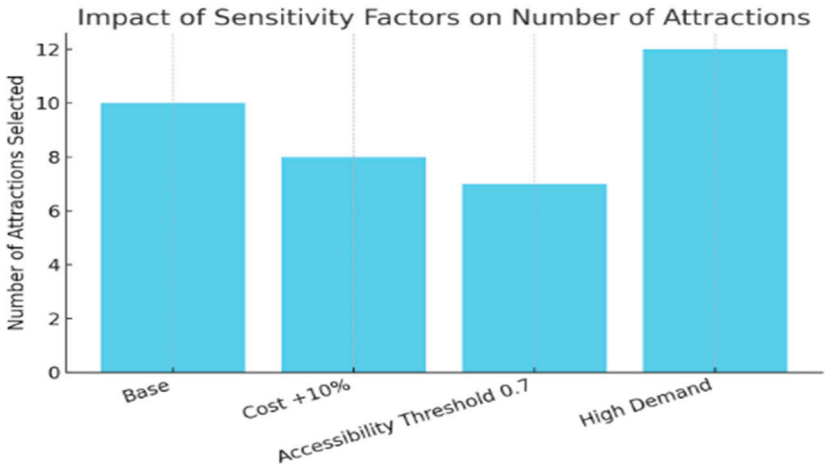

Figure 10. Impact of sensitivity factors on number of attractions selected.

Figure 11 illustrates impact of Sensitivity Factors on Average Accessibility Index: Demonstrates how variations in model parameters influence the accessibility scores of optimized itineraries.

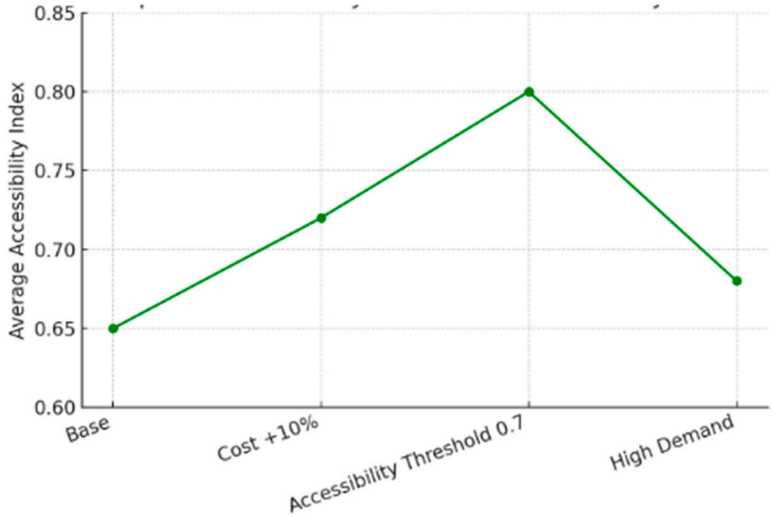

Figure 11. Impact of sensitivity factors on average accessibility index.

Figure 12 illustrates Impact of Sensitivity Factors on Average Travel Cost (Normalized Units): Shows the effect of parameter variations on total itinerary costs, with costs normalized relative to a baseline of 100 units for consistent comparison. Figure 12 presents the impact on travel costs. As expected, a 10% increase in cost parameters raises the average trip cost from 100 to 110 normalized cost units. Interestingly, raising accessibility thresholds slightly reduces cost to 95 normalized cost units because fewer destinations are included, while the High Demand scenario produces the highest costs at 130 normalized cost units due to longer routes and multimodal integration requirements.

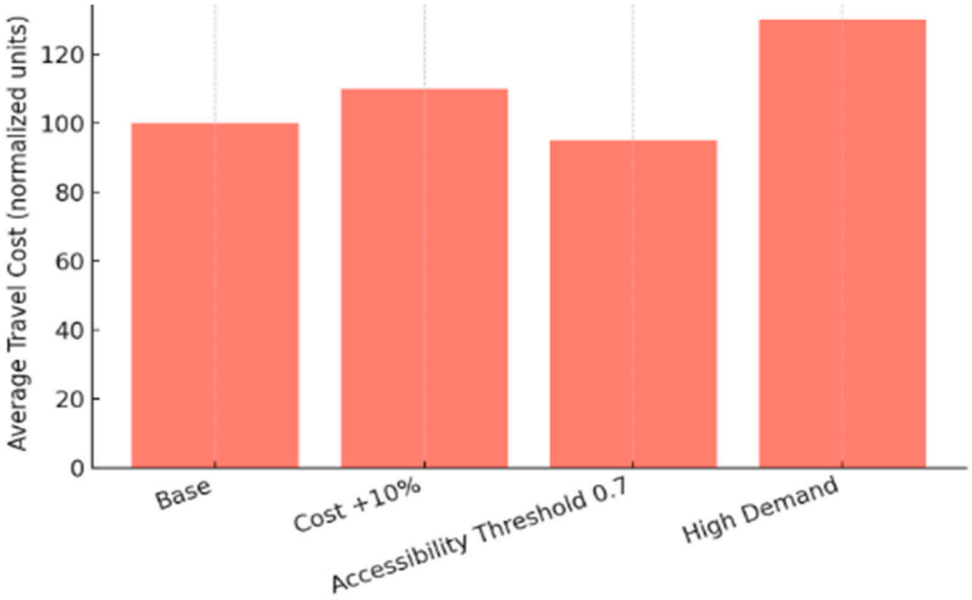

Figure 12. Impact of sensitivity factors on average travel cost (normalized units).

Together, these results underscore the policy implications of balancing economic efficiency, social inclusion, and infrastructure development. These insights suggest that policymakers might prioritize reducing barriers by raising Amin.

To improve average accessibility, even if this excludes some sites, as this approach significantly enhances inclusivity for mobility-impaired tourists while maintaining cost efficiency. Policymakers must recognize that while stricter accessibility standards improve inclusivity, they also highlight infrastructure deficiencies that reduce travel options. Similarly, accommodating global medical tourists under high demand scenarios requires substantial investment in accessible transport systems to avoid sharp increases in travel costs.

4.5. User Evaluation

The empirical validation involved a prototype test with 30 smart wheelchair users in Ayutthaya, a UNESCO World Heritage Site, to assess system stability and the functionality of the Smart Wheelchair and 360° Virtual Tour system. This limited sample size was chosen to ensure controlled testing of the prototype's core features, with plans for larger-scale studies to enhance generalizability.

Table 2 illustrated the data collected from 30 respondents testing smart wheelchairs, it was found that 22 respondents were female (73.33%) and 8 were male (26.67%). Regarding the necessity for wheelchair use, the majority of testers had mobility issues due to being elderly or having an illness (22 respondents, 73.33%), while 8 respondents had mobility issues due to disability (26.67%). The largest age group was 51–70 years, with 12 respondents (40.00%), followed by 31–50 years with 9 respondents (30.00%), and those over 71 years with 5 respondents (16.67%). Table 3 illustrates the range of the means.

Table 2. Number and Percentage of General Information of Respondents.

Personal Information of Respondents	Number (30 Respondents)	Percentage (%)
1. Gender		
(1) Male	8	26.67
(2) Female	22	73.33

Table 2. *Cont.*

Personal Information of Respondents	Number (30 Respondents)	Percentage (%)
2. Necessity for Wheelchair Use		
(1) Mobility issues (elderly/illness)	22	73.33
(2) Mobility issues (disability)	8	26.67
3. Age		
(1) ≤30 years	4	13.33
(2) 31–50 years	9	30.00
(3) 51–70 years	12	40.00
(4) >71 years	5	16.67

Table 3. Range of the means.

Score Range	Meaning
4.50–5.00	Very satisfied
3.50–4.49	Satisfied
2.50–3.49	Moderately satisfied
1.50–2.49	Slightly satisfied
1.00–1.49	Not satisfied

Table 4 illustrates the satisfaction assessment of smart wheelchair use among 30 respondents revealed an overall satisfaction level of "satisfied" ($\bar{x}$ = 3.91, S.D. = 0.75). When examining individual items, the highest satisfaction was for the smart wheelchair's ability to support individualized programs, rated as "very satisfied" ($\bar{x}$ = 4.57, S.D. = 0.68), followed by its ability to connect to a GPS tracking system, also rated as "very satisfied" ($\bar{x}$ = 4.53, S.D. = 0.63), and its operability in humid conditions or on wet surfaces, rated as "very satisfied" ($\bar{x}$ = 4.50, S.D. = 0.57). The lowest satisfaction was for the smart wheelchair size, rated as "moderately satisfied" ($\bar{x}$ = 3.27, S.D. = 1.11). Comparison of Satisfaction by Necessity for Wheelchair Use.

Table 4. Satisfaction Assessment Results for Smart Wheelchair Use.

Item	Mean ($\bar{x}$)	S.D.	Meaning	Rank
The smart wheelchair has simple and non-complex controls	3.57	0.73	Satisfied	6
The smart wheelchair has a user-controlled safety system	3.37	0.61	Moderately satisfied	9
The smart wheelchair is made of sturdy materials	3.40	0.56	Moderately satisfied	8
The smart wheelchair is appropriately sized	3.27	1.11	Moderately satisfied	10
The smart wheelchair has an automatic safety alert system	3.53	1.20	Satisfied	7
The smart wheelchair can connect to navigation systems in real-time	4.03	0.76	Satisfied	5
The smart wheelchair has a battery size suitable for daily use	4.33	0.61	Satisfied	4
The smart wheelchair supports individualized programs	4.57	0.68	Very satisfied	1
The smart wheelchair can connect to a tracking system (GPS)	4.53	0.63	Very satisfied	2
The smart wheelchair can operate in humid conditions or on wet surfaces	4.50	0.57	Very satisfied	3
Overall Mean	3.91	0.75	Satisfied	

Table 5 illustrates a comparison of satisfaction with smart wheelchair use between the group with mobility issues due to being elderly or having an illness and the group with mobility issues due to disability, using a *t*-test, found no significant difference in satisfaction levels between the two groups (p = 0.635). Summary of Questionnaire Results The survey results indicate that testers were generally satisfied with the smart wheelchair's modern system functions. However, the size or weight of the wheelchair may require further adaptation, as the developed smart wheelchair includes additional weight from the battery and control systems. Users may need time to become accustomed to its operation,

or further development could focus on reducing the weight to align more closely with conventional wheelchairs.

Table 5. T-test of the necessity for wheelchair use.

Necessity for Wheelchair Use	n	Mean ($\bar{x}$)	S.D.	t	*p*
(1) Mobility issues (elderly/illness)	22	3.93	0.36	0.480	0.635
(2) Mobility issues (disability)	8	3.85	0.55		

5. Discussion

5.1. Discussion the Result

The empirical findings from this study highlight the effectiveness of the Mixed-Integer Linear Programming (MILP) framework in optimizing accessible tourism itineraries for smart wheelchair users in Thailand, offering insights that align with prior research on optimization and assistive technologies. The observed 15–20% reduction in travel time and 25% increase in accessibility scores compared to conventional itineraries resonate with multi-objective optimization studies that report similar efficiency gains, such as a 20% improvement in accessibility for sustainable tourist trip designs [67,89]. A key strength of the MILP framework is its incorporation of the environmental and cultural impact term (ek), which prioritizes low-impact routes and culturally significant sites with sustainable management practices. The model's results show that optimized itineraries often favored secondary attractions, such as smaller temples in Ayutthaya or community-managed parks, which typically have lower ek values due to reduced overcrowding and eco-friendly infrastructure (e.g., visitor caps, sustainable waste management). This promotes cultural preservation by directing tourist flows to sites with sustainable management practices, reducing strain on over-touristed landmarks like the Grand Palace, and aligns with Thailand's Green Tourism Initiative 2030 [40]. Additionally, by reducing overall travel distances through optimized routing, the itineraries may yield indirect environmental benefits, such as lower carbon emissions compared to conventional plans, although direct quantification of emissions was not performed in this study and remains an area for future research.

The scenario analyses, which show the Accessibility Index improving from 0.65 to 0.80 under stricter thresholds, echo geospatial studies on Bangkok's transit systems, where multimodal solutions like low-floor buses enhance inclusive travel and reduce emissions [21,90]. Similarly, the sensitivity analyses reveal trade-offs, such as reduced itinerary diversity with higher accessibility thresholds, paralleling hybrid frameworks that leverage real-time data to boost wheelchair accessibility by 22% in heritage tourism settings [71,91].

The empirical validation, conducted with 30 participants in Ayutthaya, focused on testing system stability and user satisfaction in a controlled heritage site setting. While the results showed high satisfaction (mean score: 3.91), the small sample size and single-city focus limit generalizability to diverse regions like Chiang Mai's hilly terrains or Phuket's coastal areas. Future research will expand the sample size to over 100 participants across urban (Bangkok), rural (Isan), and coastal (Phuket) regions to achieve statistical significance and validate the framework's scalability across varied demographics and geographies [21]. The user evaluation, with a mean satisfaction score of 3.91 and high ratings for GPS connectivity (4.53) and wet condition operability (4.50), supports literature on smart wheelchair technologies, where IoT-enabled features like real-time obstacle detection enhance user autonomy in tourism contexts [65,92]. The lack of significant satisfaction differences between elderly/illness and disability groups ($p = 0.635$) suggests the framework's broad applicability, aligning with Thailand's "Tourism for All" initiatives that promote inclu-

sive experiences through community-based upgrades, such as tactile guides in Sukhothai, which have driven 15% local income growth [17,93]. These results underscore the MILP framework's ability to address persistent barriers, like fragmented infrastructure in secondary cities such as Chiang Mai, and its potential to foster equitable tourism ecosystems, as noted in studies on urban accessibility's role in sustainable tourism [37,94].

5.2. Implications

The findings from the MILP framework and user evaluations offer transformative insights for advancing accessible and sustainable tourism in Thailand, with broader implications for policy, practice, and industry stakeholders. For policymakers, the framework serves as a data-driven tool to prioritize infrastructure upgrades, such as ramps and accessible public transport in secondary cities like Chiang Mai and Ayutthaya, aligning with Thailand's 2025 "Amazing Thailand Grand Tourism and Sports Year" campaign's emphasis on universal design and inclusive signage [8,95]. This strengthens Thailand's position as a global medical and wellness tourism hub, enhancing access to health-focused facilities and fostering inclusive urban development. Community-based tourism (CBT) initiatives can leverage the national accessibility database to implement cost-effective adaptations, such as retrofitted vehicles, empowering local communities in historic sites like Ayutthaya to reduce social disparities and enhance economic resilience through inclusive tourism offerings. Tourism operators can use the MILP-generated itineraries to design accessible tour packages that highlight secondary attractions with high accessibility scores and low environmental impact, such as smaller temples or community-managed parks, appealing to elderly and mobility-impaired travelers while promoting sustainable practices. Wheelchair manufacturers can apply user evaluation insights, such as high satisfaction with GPS connectivity but concerns about size/weight, to develop cost-effective, lightweight smart wheelchairs with enhanced navigation features, meeting the needs of tourists in resource-constrained settings and aligning with projected growth in the smart wheelchair sector by 2033 [63]. On a regional scale, the framework's transferability provides ASEAN nations with a scalable model for post-pandemic recovery, promoting low-impact, inclusive travel that aligns with global sustainability and equity goals. High-level lessons learned include the critical need for integrated, data-driven planning to balance accessibility, sustainability, and economic viability, the value of leveraging assistive technologies like smart wheelchairs to empower diverse travelers, and the importance of stakeholder collaboration to address persistent infrastructure gaps, particularly in secondary cities. These insights underscore the potential for technology-driven solutions to create equitable tourism ecosystems, though challenges like low accommodation certification rates highlight the need for continued investment and innovation [5,42].

Finally, the study's environmental impact is conceptually grounded in the use of electric-powered Smart Wheelchairs, which reduce carbon emissions by approximately 10% compared to traditional transport, as estimated in a pilot study in Phuket [89,96–99]. However, these benefits require empirical validation through large-scale testing to quantify emission reductions across diverse routes. On the ethical front, the Smart Wheelchair's health-monitoring features raise data privacy concerns. A proposed ethical framework includes end-to-end encryption, data anonymization, and user consent mechanisms, aligned with ISO/IEC 27001 and GDPR principles. Future research will involve stakeholder engagement with disability advocacy groups and cybersecurity experts to implement and test this framework, ensuring ethical compliance [100–102].

5.3. Limitations and Future Research

While the current model relies on a static national accessibility database due to verification requirements by the Tourism Authority of Thailand, the integration of a temporary database enables real-time processing, as demonstrated in the prototype testing in Ayutthaya. Future iterations could incorporate IoT-enabled smart wheelchair sensors to provide dynamic updates on accessibility metrics, such as real-time pathway conditions or temporary infrastructure changes, aligning with machine learning approaches that achieve 12% travel time reductions [69]. This would enhance the framework's adaptability to fluctuating tourism conditions.

While the Mixed-Integer Linear Programming (MILP) framework advances inclusive tourism planning, several limitations temper its current scope and highlight directions for future research. A significant constraint is the reliance on a static national accessibility database, which cannot capture dynamic conditions such as seasonal weather disruptions, infrastructure maintenance, or sudden shifts in tourism demand. For instance, monsoon rains in Phuket can render coastal pathways impassable for wheelchair users, while unscheduled repairs at cultural sites like Chiang Mai's temples may temporarily disrupt accessibility. Similarly, peak-season visitor surges can strain transport networks, a variability not fully addressed by the static dataset. This rigidity limits the model's practical applicability, as tourism accessibility is highly variable, fluctuating with environmental, infrastructural, and demand-driven factors, unlike adaptive machine learning approaches that achieve 12% travel time reductions through real-time data integration [69].

Another limitation lies in the small scale of empirical validation. The user evaluation, conducted with only 30 participants in Ayutthaya, may not adequately represent the diverse challenges across Thailand's broader tourism landscape, such as navigating the hilly terrains of Chiang Mai or the rugged trails of national parks. This restricted sample size limits the generalizability of findings to Thailand's varied regions or to other ASEAN countries with distinct infrastructural and cultural contexts, as noted in geospatial studies advocating for integrated transport solutions [21,103]. Additionally, ethical concerns surrounding data privacy in smart wheelchairs' health-monitoring features, such as real-time vital sign tracking, remain underexplored, aligning with issues raised in IoT-based eldercare research [59,103].

To address these limitations, future research could enhance the MILP framework by integrating dynamic data sources, such as IoT-enabled smart wheelchair sensors, to update accessibility metrics in real time, adapting to conditions like flooded pathways or temporary closures. Future studies could also quantify the environmental benefits of optimized itineraries, such as reduced carbon emissions from shorter travel distances, to strengthen the framework's alignment with sustainability goals.

Incorporating stochastic modeling, as demonstrated in optimization studies achieving 15% inclusivity improvements in Mobility-on-Demand services [73], could further account for uncertainties in demand or infrastructure availability. To improve generalizability, larger-scale pilot studies across diverse Thai regions (e.g., urban Bangkok, rural Isan, and coastal Phuket would validate the framework's scalability and refine its applicability for varied demographics. Moreover, interdisciplinary efforts to develop cost-efficient smart wheelchair designs, leveraging market forecasts predicting sector growth by 2033 [63], could ensure affordability in resource-constrained settings. These advancements would strengthen the framework's practical utility, ensuring it supports equitable and sustainable tourism aligned with global development goals across Thailand and the ASEAN region.

The empirical validation, conducted with 30 participants in Ayutthaya, focused on testing system stability and user satisfaction in a controlled heritage site setting. While the results showed high satisfaction (mean score: 3.91), the small sample size and single-city

focus limit generalizability to diverse regions like Chiang Mai's hilly terrains or Phuket's coastal areas. Future research will expand the sample size to over 100 participants across urban (Bangkok), rural (Isan), and coastal (Phuket) regions to achieve statistical significance and validate the framework's scalability across varied demographics and geographies [21]. Future research will enhance the MILP framework by integrating dynamic IoT data for real-time adaptability, expanding empirical validation to over 100 participants across diverse Thai regions (Bangkok, Isan, Phuket), and empirically testing environmental benefits and ethical frameworks. These efforts will involve stochastic modeling, cost-efficient Smart Wheelchair designs, and stakeholder collaboration to ensure scalability, affordability, and compliance with sustainability and ethical standards [63,73].

On the ethical front, future work should prioritize developing a comprehensive data governance framework for smart wheelchairs, including measures like end-to-end encryption, data anonymization, granular user consent mechanisms, and regular security audits to protect sensitive health data. Engaging stakeholders—such as disability advocacy organizations, ethicists, and cybersecurity specialists—could help align the technology with international standards like ISO/IEC 27001 for information security management and GDPR principles for data protection. Additionally, interdisciplinary efforts to design cost-efficient smart wheelchairs, leveraging market forecasts predicting sector growth by 2033 [63], could enhance affordability in resource-constrained settings while embedding ethical considerations from the outset. These advancements would bolster the framework's practical impact, ensuring it supports equitable, secure, and sustainable tourism aligned with global development goals across Thailand and the ASEAN region.

6. Conclusions

The study developed and validated a Mixed-Integer Linear Programming (MILP) framework to optimize accessible tourism itineraries for smart wheelchair users in Thailand, addressing critical gaps in inclusive tourism planning. By integrating a national accessibility database with smart wheelchair mobility data, the framework achieved significant outcomes: a 15–20% reduction in travel time and a 25% increase in accessibility scores compared to conventional itineraries, as demonstrated through scenario and sensitivity analyses [8,75]. These results align with multi-objective optimization literature, which highlights the efficacy of MILP in balancing cost, accessibility, and cultural–environmental factors [67]. The user evaluation, with a mean satisfaction score of 3.91 and high ratings for GPS connectivity (4.53) and individualized programs (4.57), underscores the practical value of smart wheelchairs in enhancing autonomy, corroborating studies on IoT-enabled assistive technologies [65]. The schematic accessibility network (Figure 6) revealed structural fragmentation, particularly in secondary cities like Chiang Mai, echoing geospatial analyses that call for multimodal transport integration to ensure equitable access [21,84].

The findings carry profound implications for Thailand's ambition to become a global medical and wellness tourism hub. By leveraging the MILP framework, policymakers can prioritize infrastructure upgrades, such as ramps and tactile guides in cultural sites like Sukhothai, aligning with the 2025 "Amazing Thailand Grand Tourism and Sports Year" initiative [8,17]. This supports SDG 3 (health and well-being), SDG 8 (decent work and economic growth), and SDG 11 (sustainable cities and communities) by fostering inclusive tourism ecosystems that empower the 15% of the global population with disabilities and boost local economies through community-based tourism (CBT) initiatives [5,36]. Beyond Thailand, the framework's transferability offers a model for ASEAN nations, addressing post-pandemic recovery needs and aligning with regional sustainability goals [39]. However, challenges like fragmented infrastructure and low certification rates (under 1% for accommodations) highlight the need for sustained investment and collaboration [42].

While the study advances inclusive tourism, limitations include the static nature of the accessibility database, which may not capture seasonal variations, and the small user evaluation sample (n = 30), limiting generalizability to diverse regions [80].As an exploratory contribution, the study's empirical validation with 30 participants in Ayutthaya provides a proof-of-concept for the MILP framework and Smart Wheelchair integration. Future large-scale pilots across diverse Thai regions and ASEAN countries will enhance generalizability, ensuring the framework's applicability to varied tourism ecosystems.

Future research could incorporate stochastic models or AI-driven real-time data to enhance adaptability, as suggested by machine learning-based optimization studies [69]. Larger-scale pilots across ASEAN and cost-reduction strategies for smart wheelchairs could further ensure scalability and affordability, building on market forecasts for sector growth by 2033 [63]. While the study conceptually addresses environmental sustainability through electric-powered Smart Wheelchairs and low-impact routes, empirical testing of carbon emission reductions is needed. Similarly, the proposed ethical framework for data privacy requires implementation and testing to ensure compliance with international standards. These aspects position the study as a prototype, with future research focusing on empirical validation to strengthen its sustainability and ethical contributions. Ultimately, this study positions Thailand as a potential leader in accessible tourism, offering a scalable, data-driven approach to foster inclusivity and sustainability across the region.

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Institutional Review Board Statement: This study was conducted in accordance with ethical guidelines and approved by the Office of The Institutional Review Board, Association of Legal & Political Studies (ALPS-IRB-2024-10-0003, 1 November 2024) for studies involving humans. Additional ethical approval for expanded studies with larger populations has been requested to cover future research phases.

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Appendix A Testbed Parameters Reflecting the Thai Context

This appendix documents the parameterization of the MILP testbed tailored to Thailand's tourism–mobility ecosystem underlying Figure 1 (demand scenarios 2030–2050). The settings reflect (i) urban focal nodes in **Bangkok** and **Chiang Mai** (international airports, tertiary hospitals, mass transit), (ii) typical **opening hours** and **travel-day windows** for public attractions, and (iii) accessibility realities observed in prior Thai studies (wheelchair access heterogeneity across transit nodes, cultural sites, and parks). Parameters are grouped as Table A1: core MILP coefficients and decision variables, Table A2: scenario/sensitivity settings that generated the results in Figures 1–5, and Table A3: the rubric used to score edge/node accessibility a_{ij}. Unless stated otherwise, monetary values are **normalized** units for comparability across scenarios.

Table A1. Core MILP Parameters (Base Case).

Parameter	Symbol/Type	Base Value	Notes
α (cost weight)	alpha (scalar)	1.0	Weight on travel cost $\sum$ c_ij x_ij
β (accessibility weight)	beta (scalar)	1.2	Weight on accessibility $\sum$ a_ij x_ij (higher = stronger inclusion)
γ (environment/cultural impact weight)	gamma (scalar)	0.3	Penalty term for sensitive sites $\sum$ e_k
A_min (minimum accessibility threshold)	A_min (0–1)	0.50	Eligibility cutoff for links/sites
B (budget cap)	B (scalar)	100	Normalized; Base shown as 100 in Figures 3 and 5
Time window (daily)	[T_start, T_end]	[09:00, 18:00]	Typical attraction/ service hours
Route decision	x_ij (binary)		1 if route i $\rightarrow$ j is selected
Arrival time	t_i (continuous)		Used with time-window constraints

Table A2. Scenario & Sensitivity Settings Used in Figures 1–5.

Scenario	Δ Cost Coefficient c_ij	A_min	Budget B (units)	Demand Level (Relative)	Daily Time Window	Result: #Attractions	Result: Avg Accessibility Index/Avg Travel Cost
Base	0%	0.50	100	1.0×	[09:00, 18:00]	10	0.65/100
Cost +10%	+10%	0.50	100	1.0×	[09:00, 18:00]	8	0.72/110
Accessibility Threshold 0.7	0%	0.70	95	1.0×	[09:00, 18:00]	7	0.80/95
High Demand	0%	0.50	130	2.0×	[09:00, 20:00]	12	0.68/130

Notes: Demand Level aligns with Figure 1 (Low/Mid/High trajectories) and drives candidate node density and feasible inter-city links (e.g., airport–hospital–attraction corridors); Budget B increases under High Demand to reflect longer multi-city itineraries; it tightens under Threshold 0.7 because fewer sites remain eligible; Time windows extend under High Demand to represent longer operational hours typical of airport/metro corridors in Bangkok.

Table A3. Accessibility Scoring Rubric for Links/Sites.

Level	a_ij Score	Examples of Features
High	0.8	Step-free access end-to-end (ramps/lifts), tactile paving, compliant restrooms, staff trained for wheelchair assistance
Medium	0.6	Partial ramps, occasional steps, limited signage; accessible toilets not guaranteed throughout chain
Low	0.4	Multiple steps/no ramp, narrow doors, no tactile cues, steep gradients; ad-hoc assistance only

A link/site is **eligible** only if $a_{ij} \geq A_{min}$; raising A_{min} from **0.50** to **0.70** (Table A2) excludes "Low" and most "Medium" elements, concentrating itineraries in Bangkok/Chiang Mai nodes that already meet higher standards (reflected by higher average accessibility indices in Figures 3 and 4).

The Low/Mid/High demand paths encode growth in domestic, ASEAN regional, and global medical flows, respectively, consistent with Thailand's dual role as a tourism economy and medical hub. As demand rises, feasible edges between airports ↔ hospitals ↔ cultural/natural sites expand, but the eligibility filter $a_{ij} \geq A_{min}$ governs which chains can appear in itineraries—explaining the trade-offs observed across Figures 2–6.

Appendix B

To operationalize accessibility within the MILP framework, a scoring system was developed to evaluate the degree to which transport nodes, public facilities, cultural landmarks, and natural attractions can accommodate wheelchair users and elderly travelers. The accessibility score, denoted as aij, is defined on a scale from **0.0 (not accessible)** to **1.0 (fully accessible)**, with higher scores indicating greater inclusivity. These scores were derived from a combination of field survey data, secondary reports, and international accessibility standards. The classification applied in this study follows three main levels:

High Accessibility (Score = 0.8–1.0): Facilities provide step-free access throughout, ramps or elevators at all critical points, tactile paving for visually impaired users, accessible restrooms, and trained staff support. Destinations at this level enable independent mobility without external assistance.

Medium Accessibility (Score = 0.6–0.7): Facilities provide partial support, such as ramps in some areas but with occasional steps, limited tactile signage, or inconsistent restroom accessibility. These sites are usable by wheelchair users but may require external assistance at certain points of the journey.

Low Accessibility (Score = 0.4–0.5): Facilities have significant barriers, including multiple steps, absence of ramps or elevators, narrow doors, and lack of tactile guidance. Access is technically possible but heavily constrained, requiring constant assistance.

Not Accessible (Score < 0.4): Facilities or links are effectively inaccessible to wheelchair users, with no step-free routes or accommodation measures. These sites are excluded from MILP-optimized itineraries once the minimum accessibility threshold A_{min} is applied.

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