Transportation Research Part B 195 (2025) 103192

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

Airport's optimal decisions considering non-aeronautical business, terminal capacity and alternative regulatory regimes

Yue Huai [a], Enoch Lee [b,*], Hong K. Lo [a], Anming Zhang [c]

[a] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[b] Department of Logistics and Maritime Studies, Hong Kong Polytechnic University, Hong Kong, China
[c] Sauder School of Business, University of British Columbia, 2053 Main Mall, Vancouver, BC, Canada

ARTICLE INFO

Keywords:
Non-aeronautical business
Terminal capacity expansion
Suggested arrival time
Single- vs. dual-till regulation

ABSTRACT

This study explores the optimal decisions of airports on charge, capacity, and suggested passengers' arrival time at the airport under various regulatory regimes (e.g., single- or dual-till regulation). By considering both aeronautical- and non-aeronautical businesses and further incorporating the non-linear relationship between queuing time in the check-in zone and shopping time in the retail zone, we find that unlike runway capacity expansion, where single-till regulation leads to underinvestment (as compared to the unregulated case), terminal capacity expansion is contingent upon traffic volumes. Under higher traffic volumes, terminal capacity expansion becomes less efficient in reducing the terminal congestion delay, thereby reducing the effect on expanding passengers' shopping time and concession revenue. As the revenue loss is disregarded under single-till regulation, airports would overinvest in terminal capacity under higher traffic volumes, which reverses the underinvestment tendency under lower traffic volumes. Also, single-till regulation results in a later airport arrival time suggested to passengers, for which the excess concession revenue from an earlier arrival time is overlooked. By contrast, dual-till regulation tends to attract more passengers to the airport by reducing terminal and runway delays, therefore leading to lower airport charge, shorter terminal time and higher capacity. The increased ridership and enhanced utility thus improve the overall social welfare.

1. Introduction

The COVID-19 pandemic significantly lowered the air travel demand (Sun et al., 2022), leading to substantial revenue losses for global and domestic hub airports, particularly in non-aeronautical sectors.[1] For instance, Hong Kong Airport (IATA code: HKG) experienced a 96.6% decline in retail licenses revenue in 2022 due to a 98.7% drop in passenger volume, leading to a wave of

* Corresponding author.
E-mail addresses: ceyhuai@ust.hk (Y. Huai), enoch.lee@polyu.edu.hk (E. Lee), cehklo@ust.hk (H.K. Lo), anming.zhang@sauder.ubc.ca (A. Zhang).

[1] Non-aeronautical revenues depend heavily on passenger volume, whereas aeronautical revenues depend largely on aircraft movements (airport charges on take-off and landing). While passenger flights were hit hard by the pandemic, cargo flights remained relatively strong, leading to relatively heavier impact on non-aeronautical revenues.

https://doi.org/10.1016/j.trb.2025.103192
Received 26 August 2024; Received in revised form 18 February 2025; Accepted 28 February 2025
Available online 13 March 2025

temporary airport shop closures. To rejuvenate non-aeronautical business, commercial airports have invested in various resources to restore travel demand and airport goods purchases. HKG, for instance, is expanding terminal space and implementing flight tokens[2] to reduce the hassles in security and customs checks, thereby increasing passengers' dwell time in the retail zone and concession revenue[3]. However, terminal expansion and infrastructure upgrades require significant capital investment, raising concerns about cost recovery and potential loss of social welfare. Airports may raise aeronautical charges and shop rentals, which would nevertheless lower the consumer surplus. To enhance social welfare, regulatory constraints are imposed on commercial airports (e.g., single- or dual-till regulation). Although these constraints have been extensively studied in the literature, most research uses runway capacity to represent the airport's aeronautical capacity, overlooking the impact of queuing delay in the check-in zone on passengers' dwell time in retail zones and concession revenue. In addition, concession revenue is affected by how early the airport advises the passengers to arrive before flight departure. While earlier arrival times increase dwell time and concessions (Choi, 2021), a longer dwell time can backfire as passengers may opt for other airports or travel modes (Wu et al., 2024). Surprisingly, studies have yet examined how regulatory constraints affect airport decisions on terminal capacity, encompassing factors such as check-in, security, customs counters, staffing, and recommended arrival times. This study aims to address this gap.

Over the past two decades, extensive studies have compared single-till and dual-till regulation in terms of social welfare and optimal decisions on airport capacity (Czerny, 2006; Kidokoro and Zhang, 2023a, 2022; Oum et al., 2004; Yang and Zhang, 2011; Zhang and Zhang, 2010). Single-till regulation considers the airport's profit to be generated from a unified source, ensuring that total revenue from both aeronautical and non-aeronautical services covers its total costs. On the other hand, dual-till regulation distinguishes the profits from aero- and non-aero services, requiring that the revenue from the aeronautical service covers its costs while leaving non-aeronautical profit unregulated. A major result from these studies is that single-till regulation yields higher welfare than dual-till regulation in the absence of airport congestion, whilst the result is reversed when airports experience congestion. Furthermore, when compared to unregulated, socially optimal decisions, single-till regulation results in a smaller airport capacity, while dual-till regulation leads to a greater airport capacity (Kidokoro et al., 2016; Zhang and Zhang, 2010). However, these results were obtained by assuming that the effect of airport capacity on reducing travel time cost is more pronounced for higher traffic volumes. While this holds true for runway capacity on which the earlier studies have focused, it may not reflect the reality for terminal capacity accurately.

Terminal congestion not only increases passengers' travel time cost, but also affects their purchasing behavior inside the terminal. In contrast, runway congestion occurs posterior to boarding, hence barely affecting airport concession revenues. Therefore, extrapolating insights from runway to terminal capacity presents a significant challenge as there are different variables and considerations inherent in these resources. Most of the existing concession studies failed to differentiate the delay incurred in the terminals and on the runways, hence imposing challenges to distinguish the terminal capacity decision from runway capacity decision made by airports. Few notable exceptions include (Wan et al., 2015), where a deterministic bottleneck model is applied to analyze passengers' behavior inside airport terminals. They found that incorporating the concession revenue into airport's policy decision may result in a higher airport charge aimed at attracting more business passengers, who are typically assumed to arrive at the airport later than leisure passengers. Consequently, leisure passengers are pushed to arrive at the airport even earlier, leading to longer dwell time for them. This extended dwell time increases the likelihood of purchasing airport goods, thereby boosting concession revenue. The study is among the first to explicitly address the intricate relationship between terminal congestion, airport charges and capacity expansion decisions. Passengers' dwell time in the terminal retail zone and queuing time at the check-in zone are assumed to be linearly correlated, based on the deterministic bottleneck model. Yet, the model might not reflect the realistic situation where passengers may have little interest in visiting the retail shops after a long queuing delay. To better understand passengers' shopping behavior influenced by the terminal operational performance, a more detailed exploration supported by real data is expected.

Using indoor trajectory data from HKG, Huai et al. (2024) discovered a negative and exponential correlation between dwell time at the retail zone (or "shopping time") and queuing time at the check-in zone. The nonlinear relationship suggests that hassles and queuing delays incurred in the check-in zone would significantly reduce passengers' willingness to purchase in retail shops. With the nonlinear relationship integrated into an equilibrium model which encompasses passengers, airlines and a monopolistic airport, they compared the airport decisions regarding terminal capacity and runway capacity. Unlike runway capacity, decisions on terminal capacity involve a trade-off between the revenue gain from induced traffic volume and the revenue loss from shopping time variation. More specifically, the effect of terminal capacity expansion on shopping time extension varies with the traffic volume (details to be discussed in Section 2.21), i.e., the effect of terminal capacity expansion on extending shopping time is more pronounced for lower traffic volumes and diminishes for higher traffic volumes. Consequently, this relation reverses airport decisions on terminal capacity for higher traffic volumes, e.g., by comparison with welfare-maximizing airports, profit-maximizing airports tend to invest more under lower traffic (the same as the result of runway capacity decisions in Kidokoro et al. 2016) but invest less under higher traffic volumes. The intriguing relationship between terminal capacity and shopping time points to the need for an exploration of its impact on the airport's decisions under various regulatory constraints, which has yet to be explored in the literature.

In this study, we extend the equilibrium model of Huai et al. (2024) to examine a monopolistic airport's optimal decisions regarding terminal capacity and advised arrival time to passengers under different objectives (profit- vs. welfare-maximizing) and regulatory constraints. In particular, our model incorporates the relation between terminal capacity and shopping time, which is among the first

[2] Flight token is a self-service biometric identification system, which aims to streamline the check-in, security check, customs check and boarding processes, thereby lowering the queuing delay in the check-in zone.

[3] In this paper, we use non-aeronautical revenue and "concession revenue" interchangeably.

studies to investigate how single- and dual-till regulations affect airport decisions considering the influence of shopping time on concession revenue. Single-till regulation leads to lower runway capacity and shorter dwell time in the terminal (later arrival time suggested to passengers) than the benchmark (i.e., the unregulated welfare-maximizing case). Dual-till regulation corrects the distortion of single-till regulation in runway capacity, but it exacerbates the distortion in advised arrival time (even later arrival time, thus shorter dwell time inside the terminal). For terminal capacity decisions, the distortions mirror those resulting from runway capacity decisions at lower traffic volumes. While at higher traffic volumes, terminal capacity expansion becomes less efficient in reducing the queuing time at the check-in zone, hence lowering the effect on shopping time expansion and thus concession revenue. Consequently, terminal capacity expansion has the opposite effect at higher traffic volumes, reversing the direction of distortion resulting from different regulatory constraints under lower traffic volumes. This highlights the significance of incorporating the impact of shopping time on concession revenue when comparing the two regulatory constraints. To the best of our knowledge, this study is the first to identify the volume-dependent capacity decisions under different regulatory constraints.

As a result, this study improves our understanding of non-aeronautical services in airport management in two aspects. First, by incorporating the impact of dwell time at retail zones on concession revenue, we find that, unlike runway capacity, the decisions on terminal capacity can involve a trade-off between revenue gain from traffic volume and revenue loss due to shopping time shrinkage. The relationship between terminal capacity and shopping time reverses airport decisions under higher traffic volumes, irrespective of the regulatory constraints in place. The nuanced difference between terminal and runway capacity decisions and their distinct impact on airport revenue highlights the importance of including dwell time in the analysis of airports. Second, contrary to the prevailing view that single-till regulation reduces airport charges through cross-subsidization from non-aeronautical revenue, our study reveals that the single-till regulation may lead to higher airport charges, lower investment in capacity and shorter terminal time. By contrast, dual-till regulation partially rectifies these distortions, restores welfare-maximizing results and results in higher social welfare. These insights enable airport regulators to envisage the responses of airport operators to different regulatory regimes and their resultant welfare outcomes, especially during the recovery period following the pandemic.

The rest of this paper is organized as follows. In Section 2, we set up a model that includes air passengers, airlines with market power, and a monopolistic airport operating both aeronautical and non-aeronautical services. In Section 3, the impact of two regulatory constraints (single-till and dual-till regulation) on welfare- and profit-maximizing airports are analyzed. Section 4 concludes this study.

2. Model framework and basic analysis

Our model includes air passengers, airlines, and a monopolistic airport operating both aeronautical and non-aeronautical business. The model encapsulates three stages: 1) The airport decides on the charge, capacity (terminal and runway) and advised arrival time to passengers, to maximize a certain objective (airport profit or social welfare); 2) Airlines engage in Cournot competition to maximize their profit; and 3) Passengers maximize their utility by deciding their trip demand and consumption of airport goods. To examine the subgame perfect Nash equilibrium, backward induction is used.

2.1. Passenger utility maximization

Following the non-aeronautical studies (Kidokoro et al., 2016; Kidokoro and Zhang, 2022, 2018), we formulate air passengers' utility maximization problem at the airport (Muellbauer, 1976), which is subjected to the income constraint, as follows:

$$\max U = z + u(q_0, x_1),\ \text{subject to } z + \rho_0 \cdot q_0 + p_1 \cdot x_1 = I \tag{2.1}$$

where z is the quantity of a numeraire good and U is the aggregate utility for all air passengers. Further, the utility function $u(q_0,x_1)$ is the aggregate utility function for all q_0 consumers purchasing totally x_1 amount of airport goods. $u(q_0,x_1)$ is assumed to be quasi-linear and strictly concave; ρ_0 is the full cost of the trip; q_0 is the aggregate trip demand (from the airport); x_1 is the aggregate demand for non-aeronautical services (e.g., car parking, retail), which complements the aeronautical service; p_1 is the price of non-aeronautical service; and I is the aggregate income of all air passenger choosing the airport. Then the first-order conditions of the utility maximization in

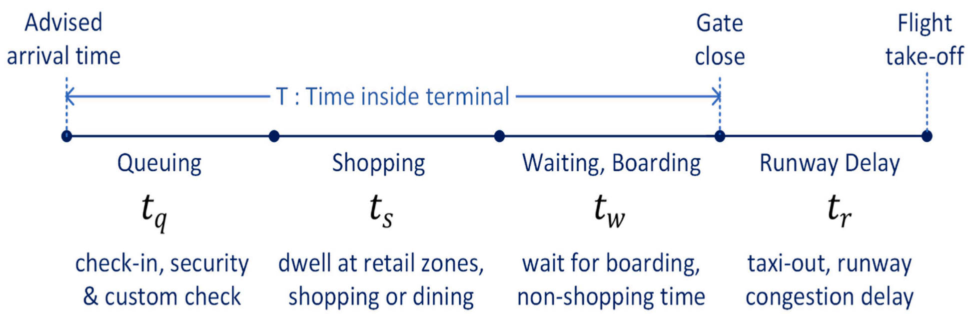

Fig. 1. Timeline of a departing passenger at the airport.

(2.1) are shown as follows:

$$\rho_0 = \frac{\partial u(q_0, x_1)}{\partial q_0} \tag{2.2}$$

$$p_1 = \frac{\partial u(q_0, x_1)}{\partial x_1} \tag{2.3}$$

Generally, airports advise passengers to arrive at the airport 2 to 4 hours before flight's scheduled departure. Once passengers arrive at the airport, they experience queuing delays at check-in counters, security check and customs (for international flights): here we denote the queuing time at the check-in zone as t_q. After passengers pass through customs, they start to dine or purchase airport concession goods in the retail zone before boarding, and the dwell time in the retail zone (shopping time) is denoted as t_s. Passengers also spend some time in the waiting lounge (next to the gate) before boarding, denoted as t_w. Hence the dwell time in the airport terminal T, which is the time between advised arrival time and gate closure (as shown in Fig. 1), can be expressed as the sum of the three time intervals, i.e., $T = t_q + t_s + t_w$.

Besides, as shown in Fig. 1, the time between gate closure and the flight take-off includes taxi-out and runway congestion delay, denoted as t_r. Following Morrison (1987), we assume that the system dynamics align with the classical M/M/1 queueing theory[4]. Specifically, passenger arrivals and flight departures follow independent Poisson arrival processes, while the service times at check-in counters, security checks, and customs collectively follow an exponential distribution, as do the service times for runway operations. The advised arrival time corresponds to the mean arrival time at check-in counters, which results in an average dwell time T. Then, the steady-state average delays of queues incurred on the runway t_r and terminal check-in zones t_q can be expressed as follows:

$$t_r = \beta_1 \cdot \frac{q_0/w}{K \cdot (K - q_0/w)}, \quad t_q = \beta_2 \cdot \frac{q_0}{C \cdot (C - q_0)} \tag{2.4}$$

respectively, where K denotes the runway capacity (i.e., service rate of runway operations for this study), C denotes the terminal capacity (i.e., service rate of the check-in counters, security and customs checks inside the airport terminal for this study), w denotes the seat capacity of the plane, and hence q_0/w is used to gauge the arrival rate of flights (assuming Poisson arrival). β_1,β_2 are parameters that can be calibrated from passenger volume, runway traffic, flight delay and passenger dwelling time data. It is worth noting that the M/M/1 steady state queuing delay presumes that the arrival rate of passengers at the check-in zone q_0 and flights at the runway q_0/w will be lower than the capacities (or service rates) of terminal C and runway K, respectively. The stochastic arrival of passengers and flights causes delays and becomes much more severe when the arrival rate approaches capacity (service rate). This reflects the situation for most of the hub airports that operate at full capacity, where a tiny increase in the passenger volume would significantly worsen the performance with a much longer delay (Basso and Zhang, 2007a; Brueckner, 2002; Daniel, 1995). Consequently, the terminal time represents the average time the air passengers stay in the terminal.

As passengers are assumed to arrive at the airport following Poisson arrival process, the advised arrival time (decided by the airport) is the average arrival time for passengers with different trip purposes (Wan et al., 2015) or risk preferences (Lee et al., 2024; Lo et al., 2006) may reserve different time budgets and arrive at the airport at different times. For a more detailed sketch of homogeneous arrival time by different passengers at the airport, the bottleneck model (Li et al., 2024a, b) can further be integrated into the modelling framework. Also, with more detailed data regarding the delay incurred in different locations of the airport (e.g., check-in counter, security check, customs, boarding gate, runway), the sequential relationship between terminal congestion and runway congestion can be explicitly revealed (Karanki and Zhang, 2025). For instance, once the runway service rate reaches capacity, increasing the terminal service rate could not reduce the runway queuing delay and passengers may experience a longer delay in the terminal (to wait for the departure). Under that situation, passengers may also purchase food and beverage to relieve the stress arising from the extra waiting time. As the intricate interaction between terminal and runway congestion requires more empirical evidence to validate (Wan et al., 2015), a separate study is needed to uncover their sequential relationship.

With the indoor trajectory data from HKG, Huai et al. (2024) discovered a non-linear relationship (negative exponentially correlated) between the dwell time in the retail zones (shopping time) t_s and queuing time in the check-in zone t_q, expressed as follows:

$$t_s = \exp\left(\beta_3 \cdot \left(T - \beta_4 \cdot t_q\right)\right) \tag{2.5}$$

where the positive parameter β_3 captures the impact of terminal time T on shopping time t_s, which an earlier arrival time allows a longer dwell time in the retail zone (Wu et al., 2024) and $\beta_3 \cdot \beta_4$ depicts the impact of queuing time t_q on shopping time t_s. The negative and exponential correlation indicates that the hassles incurred in the check-in zone significantly reduce passengers' energy and interest in visiting the airport shops. Parameters β_3,β_4 can also be calibrated with t_s and t_q obtained from the airport data. Also, it is worth noting that the space allocation of terminal retail zones significantly affects passengers' dwell time and shopping behavior inside the

[4] Heterogeneity in passenger attributes, such as risk aversion, travel time valuation, terminal activity preferences (e.g., shopping, lounge use), and ground access variability, can be modeled via concave utility functions to refine consumer surplus calculations. However, this approach introduce substantial analytical complexity and distract from the paper's primary focus. In the absence of granular empirical data on passenger profiles, robust assumptions about these heterogeneities and their policy implications might not be reliable. We highlight that exploring these dynamics represents a promising avenue for future research.

terminal. For a detailed sketch of their intricate relationship, the shop locations, walking speed and distribution of passengers' travel time budget in the retail zone (Hsu and Chao, 2005) can further be incorporated into the modeling framework.

Empirical studies found that passengers have distinct perceptions of different types of time spent in airport terminals (Choi and Park, 2022; Graham, 2009; Lin and Chen, 2013). In general, queuing in the check-in zone increases passengers' stress and anxiety level (Chen et al., 2020; Choi and Park, 2022). By contrast, shopping or dining in the retail zone provides some relief to passengers, hence the queuing incurred a higher travel cost (value of travel time) as compared with shopping, i.e., $v_q > v_s$. Also, some empirical studies indicated that passengers feel more delightful in shopping or dining than sitting in the waiting lounge (Chung and Ku, 2023; Tymkiw, 2017), especially during flight delays and extreme weather. Thus, shopping time is less costly as compared to waiting time in front of the boarding gate, i.e., $v_w > v_s$. In this study, we consider queuing as the most costly and stressful time for passengers, followed by waiting and shopping, i.e., $v_q > v_w > v_s$. Then the travel time cost inside the terminal can be expressed as a linear combination of the three time periods, weighted by value of travel times, $c_t = v_q \cdot t_q + v_s \cdot t_s + v_w \cdot t_w$. Similarly, the runway delay cost $c_r = v_r \cdot t_r$, where v_r denotes the value of time on aircraft (taxi-out and waiting for flight take-off). Then the full cost of the trip can be expressed as the sum of the travel time cost inside terminal c_t, runway delay cost c_r (outside terminal) and ticket price p_0, as follows:

$$\rho_0 = c_t + c_r + p_0 \tag{2.6}$$

where the ticket price p_0 results from airline's Cournot competition (revealed in Section 2.2).

2.1.1. Impact of terminal time and investment in terminal and runway capacity

With the relation among dwelling times (queuing t_q, shopping t_s, waiting t_w and runway delay t_r), airport decision variables (terminal capacity C, runway capacity K and terminal time T) and trip demand q_0 revealed in (2.4)-(2.5), we derive the first- and second-order derivatives with respect to (w.r.t.) trip demand and decision variables C, T and K. In line with Kidokoro and Zhang (2023b), a higher trip demand increases the queuing delay, i.e., $\frac{\partial t_q}{\partial q_0} = (C - q_0)^{-2} > 0$, thus reducing the dwell time in the retail zone, i.e., $\frac{\partial t_s}{\partial q_0} = -\beta_3\beta_4 t_s \cdot \frac{\partial t_q}{\partial q_0} < 0$. From the airport's perspective, terminal capacity expansion lowers the queuing time, i.e., $\frac{\partial t_q}{\partial C} = \frac{q_0(q_0-2C)}{C^2} \cdot \frac{\partial t_q}{\partial q_0} < 0$, which allows passengers a longer shopping time in the retail zone, i.e., $\frac{\partial t_s}{\partial C} = -\beta_3\beta_4 t_s \cdot \frac{\partial t_q}{\partial C} > 0$. Besides, an earlier advised arrival time (longer terminal time T) also extends passengers' dwell time in the retail zone, i.e., $\frac{\partial t_s}{\partial T} = \beta_3 t_s > 0$. Similar to terminal capacity expansion, runway capacity expansion also reduces the runway delay, i.e., $\frac{\partial t_r}{\partial K} = \frac{q_0(q_0-2wK)}{(wK-q_0)^2 \cdot K^2} < 0$.

We further explore the effect of terminal capacity investment on queuing time reduction and shopping time expansion under different traffic volumes. Consistent with previous findings (Kidokoro et al., 2016), the effect of terminal capacity expansion on queuing time reduction ($\frac{\partial t_q}{\partial C} < 0$) is more pronounced under higher traffic volumes, i.e., $\frac{\partial}{\partial q_0}\left(\frac{\partial t_q}{\partial C}\right) = -2(C - q_0)^{-3} < 0$. In contrast, the effect on shopping time expansion is contingent upon traffic volume, as follows:

$$\frac{\partial^2 t_s}{\partial q_0 \partial C} = \underbrace{\frac{\beta_3\beta_4 \cdot t_s}{(C-q_0)^4 \cdot C^2}}_{>0} \cdot \underbrace{\left(\beta_3\beta_4 \cdot q_0(q_0 - 2C) + 2C^2(C - q_0)\right)}_{\text{depends critically on } q_0 \text{ and } \overline{q_0}},$$

$$\overline{q_0} = C \cdot \frac{(\beta_3\beta_4 + C) - \sqrt{\beta_3^2\beta_4^2 + C^2}}{\beta_3\beta_4}, \quad \begin{cases} \text{when } 0 < q_0 < \overline{q_0}, & \frac{\partial}{\partial q_0}\left(\frac{\partial t_s}{\partial C}\right) > 0, \quad \textit{more pronounced} \\ \text{when } q_0 < \overline{q_0} < C, & \frac{\partial}{\partial q_0}\left(\frac{\partial t_s}{\partial C}\right) < 0, \quad \textit{diminishing} \end{cases} \tag{2.7}$$

The effect of terminal capacity expansion on shopping time, i.e., $\frac{\partial t_s}{\partial C}$, and traffic volume q_0 follows a diminishing relationship (Huai et al., 2024). As shown in (2.7), for lower traffic volumes ($0 < q_0 < \overline{q_0}$), the effect of terminal capacity expansion on extending shopping time is more pronounced with volume, i.e., $\frac{\partial}{\partial q_0}\left(\frac{\partial t_s}{\partial C}\right) > 0$; whereas for higher traffic volumes, ($\overline{q_0} < q_0 < C$), the effect is diminishing with volume, i.e., $\frac{\partial}{\partial q_0}\left(\frac{\partial t_s}{\partial C}\right) < 0$. Here $\overline{q_0}$ corresponds to the critical condition where $\frac{\partial}{\partial q_0}\left(\frac{\partial t_s}{\partial C}\right) = 0$, i.e., the shopping time would not be increased by terminal capacity expansion under traffic volume $\overline{q_0}$.

With the diminishing relationship between terminal capacity expansion and shopping time developed, we further investigate the effect of terminal capacity expansion on passenger's travel time cost under different traffic volumes, as follows:

$$\frac{\partial^2 c_t}{\partial q_0 \partial C} = (v_q - v_w)\cdot\frac{\partial^2 t_q}{\partial q_0\partial C} + (v_s - v_w)\cdot\frac{\partial^2 t_s}{\partial q_0 \partial C}$$
$$= \frac{\underbrace{2(q_0 - C)\left((v_q - v_w) + \beta_3\beta_4 t_s(v_w - v_s)\right)}_{<0}}{(C-q_0)^4} + \frac{\underbrace{q_0(2C - q_0)\cdot\beta_3^2\beta_4^2\cdot t_s(v_w - v_s)}_{>0}}{C^2\cdot(C-q_0)^4},$$
$$\overline{\overline{q_0}} = C - \frac{\frac{\partial c_t}{\partial t_q} + \sqrt{\left(\frac{\partial c_t}{\partial t_q}\right)^2 + \left(\frac{\partial t_s}{\partial t_q}\right)^2\cdot\frac{\beta_3\beta_4(v_w - v_s)^2(\beta_3\beta_4 - 2C)}{C^2}}}{\frac{\partial t_s}{\partial t_q}\cdot\frac{\beta_3\beta_4(v_w - v_s)}{C^2}}, \Rightarrow \begin{cases} \text{when } 0 < q_0 < \overline{\overline{q_0}}, & \frac{\partial}{\partial q_0}\left(\frac{\partial c_t}{\partial C}\right) < 0 \\ \text{when } q_0 < \overline{\overline{q_0}} < C, & \frac{\partial}{\partial q_0}\left(\frac{\partial c_t}{\partial C}\right) > 0 \end{cases} \tag{2.8}$$

Since the terminal capacity expansion C lowers air passengers' travel time cost inside the airport terminal c_t, i.e., $\frac{\partial c_t}{\partial C} = (v_q - v_w)\cdot\frac{\partial t_q}{\partial C} + (v_s - v_w)\cdot\frac{\partial t_s}{\partial C} = \underbrace{\left((v_q - v_w) + \beta_3\beta_4 t_s(v_w - v_s)\right)}_{>0 \text{ as } v_q > v_w > v_s}\cdot\underbrace{\frac{q_0(q_0 - 2C)}{C^2(C-q_0)^2}}_{<0} < 0$, as shown in (2.8), the effect of terminal capacity expansion on terminal cost reduction is contingent upon traffic q_0. Here $\bar{q}_0$ corresponds to the critical condition where $\frac{\partial}{\partial q_0}\left(\frac{\partial c_t}{\partial C}\right) = 0$, i.e., passengers' terminal time cost would not be reduced by terminal capacity expansion under traffic volume $\bar{q}_0$. For lower traffic volumes ($0 < q_0 < \bar{q}_0$), the effect is more pronounced with more passengers in terminal, i.e., $\frac{\partial}{\partial q_0}\left(\frac{\partial c_t}{\partial C}\right) < 0$. For higher traffic volumes ($q_0 < \overline{\overline{q_0}} < C$), the effect is diminishing, i.e., $\frac{\partial}{\partial q_0}\left(\frac{\partial c_t}{\partial C}\right) > 0$. Hence, the relationship between terminal capacity expansion and passengers' travel time cost reduction is also U-shaped. In essence, terminal capacity expansion differs from runway expansion as it affects passengers' purchasing behavior inside the terminal, which reverses the airport's decisions regarding terminal capacity under higher traffic volumes, as revealed in Section 3.

2.2. Airline Cournot competition

Given airport decisions on different types of resources and assuming passenger utility-maximizing behavior, airlines engage in Cournot competition in the second stage of our model. To simplify the analysis, we assume N carriers with market power providing homogeneous services for passengers. The profit maximization problem of an airline j can be expressed as follows:

$$\max \pi_j = (p_0 - \tau)\cdot q_j = (\rho_0 - c_t - c_r - \tau)\cdot q_j \tag{2.9}$$

where τ is the uniform airport aeronautical charge, q_j is the airline j's market share, and $q_0 = \sum_{j=1}^{N} q_j$. Assuming the N airlines are symmetric, then $q_j = \frac{q_0}{N}$. Hence the first-order condition for the airline's profit-maximization problem is expressed as: $\frac{\partial \pi_j}{\partial q_j} = p_0 - \tau + \frac{q_0}{N}\cdot\frac{\partial p_0}{\partial q_0} = 0$. With (2.6), the optimal ticket fare that maximizes airline's profit can be expressed as:

$$p_0 = \tau - \frac{q_0}{N}\cdot\frac{\partial p_0}{\partial q_0} = \tau \underbrace{- \frac{q_0}{N}\cdot\left(\frac{\partial \rho_0}{\partial q_0} - \frac{\partial c_t}{\partial q_0} - \frac{\partial c_r}{\partial q_0}\right)}_{\text{excess profit from competition}} \tag{2.10}$$

According to (2.2), $\frac{\partial \rho_0}{\partial q_0} = \frac{\partial^2 u}{\partial q_0^2}$. As the utility function $u(q_0, x_1)$ is strictly concave, we have $\frac{\partial^2 u}{\partial q_0^2} < 0$. Also, the travel time cost c_t and runway delay c_r increases with traffic volume, hence $\frac{\partial c_t}{\partial q_0} > 0$, $\frac{\partial c_r}{\partial q_0} > 0$. Thus, $-\frac{q_0}{N}\left(\frac{\partial \rho_0}{\partial q_0} - \frac{\partial c_t}{\partial q_0} - \frac{\partial c_r}{\partial q_0}\right) > 0$, which represents the excess profit from the Cournot competition and associates with airline's market power (e.g., less busy routes are served by few carriers, i.e., smaller N, each airline holds a larger market power, thus resulting in higher ticket prices than busy routes). Substituting the optimal ticket fare in (2.10) into (2.6), we have $\rho_0 = \tau - \frac{q_0}{N}\cdot\left(\frac{\partial \rho_0}{\partial q_0} - \frac{\partial c_t}{\partial q_0} - \frac{\partial c_r}{\partial q_0}\right) + c_t + c_r$.

Total differentiating the full cost of the trip ρ_0 from above and (2.2), and equating the differentiation results, the first-order derivative of traffic volume q_0 w.r.t. C, T and K can be expressed as follows:

$$\frac{dq_0}{dC} = \frac{dq_0}{d\tau}\cdot\left(\underbrace{\frac{\partial c_t}{\partial C}}_{>0} + \underbrace{\frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial C}}_{>0 \text{ or } <0}\right), \quad \frac{dq_0}{dT} = \frac{dq_0}{d\tau}\cdot\left(\underbrace{\frac{\partial c_t}{\partial T}}_{>0} + \underbrace{\frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial T}}_{>0}\right), \quad \frac{dq_0}{dK} = \frac{dq_0}{d\tau}\cdot\left(\underbrace{\frac{\partial c_r}{\partial K}}_{<0} + \underbrace{\frac{q_0}{N}\cdot\frac{\partial^2 c_r}{\partial q_0\partial K}}_{<0}\right) \tag{2.11}$$

The detailed derivations are shown in Appendix A. It has been demonstrated that $\frac{dq_0}{d\tau} < 0$, where a higher airport charge reduces trip demand. Thus, the impact of expanding three types of resources (C, T and K) on trip demand depends on the terms inside the brackets in (2.11).

In line with Kidokoro and Zhang (2023b), we have $\frac{dq_0}{dK} > 0$, i.e., expanding runway capacity increases the trip demand. In contrast, expanding terminal capacity or dwell time in airport terminals does not guarantee trip demand increment. At higher traffic volumes, the incremental terminal capacity cannot dissipate the induced trip demand, which worsens the quality of services in the check-in zone, thereby increasing the travel cost and lowering the trip demand (diminishing relation). A longer dwell time in the terminal allows passengers a longer shopping time in the retail zone, thereby shortening the waiting time and travel time cost, which induces a higher trip demand. For higher traffic volumes, the induced demand cannot be served timely in the check-in zone, which increases the travel cost and lowers the trip demand. Hence, there must exist an optimal terminal capacity and advised arrival time to passengers to maximize the trip demand. In summary, airport authorities need to balance between the induced demand from terminal capacity expansion or longer available shopping time (from earlier arrival time advised to passengers) and reduced demand due to queuing time surge in the check-in zone.

2.3. Optimal decisions of an airport without regulations

In the first stage, the monopolistic airport decides on aeronautical charge τ, terminal capacity C, runway capacity K and passenger dwell time T to maximize a certain objective, i.e., airport profit or social welfare (including passengers' utility and airlines' profit). In the following, we derive the airport's optimal decisions with no regulatory constraints imposed.

2.3.1. Non-aeronautical services, airport profit and social welfare

Apart from aeronautical services, the airport also provides non-aeronautical services, with revenue positively correlated to the duration of passengers' stay in the retail zone (Wu et al., 2024). Also, a higher traffic volume increases the number of visits and the likelihood of purchases in airport retail shops, allowing the airport to charge higher rents. Following Kidokoro et al. (2016), we assume the airport employs a take-it-or-leave-it strategy to concessionaires, fully capitalizing on the locational premium in shop rents and leaving concessionaires with zero profits. In this study, the concession surplus R is modeled as a monotonically increasing function with passengers' shopping time t_s and traffic volume q_0, expressed as follows:

$$\frac{\partial R}{\partial t_s} > 0, \qquad \frac{\partial R}{\partial q_0} > 0 \tag{2.12}$$

The airport revenue comes from aeronautical service provided to airlines (airport charge) and concession surplus from non-aeronautical services provided to concessionaires. Then the airport profit π_o can be expressed as the residual revenue after paying the incremental fixed and operating costs of terminal and runway capacity expansion c_{KC}, as follows:

$$\pi_o = \tau \cdot q_0 + R - c_{KC} \tag{2.13}$$

where the c_{KC} is a function of the level of investment in terminal capacity C and runway capacity K. For simplicity, the terminal space is assumed to be fixed and the cost of providing terminal space to retailers and concessionaires is normalized to zero in this study.

From the airport authority's perspective, apart from airport profit, airline profit and passenger utility also affect their decisions. In this study, we define the social welfare as the sum of airport profit π_o in (2.13), airline profit $\sum_j \pi_j$ in (2.9) and air passengers' utility U in (2.1), as follows:

$$SW = U + \sum_j \pi_j + \pi_o = z + u + (p_0 - \tau) \cdot q_0 + q_0 \cdot \tau + R - c_{KC} \tag{2.14}$$

2.3.2. Comparison between welfare- and profit-maximizing airport decisions (unregulated)

With the airport profit and social welfare defined above, we derive the optimal decisions made by profit- and welfare-maximizing airports regarding terminal capacity, advised arrival time (dwell time inside the terminal) and runway capacity. The first-order conditions of three types of resources employed by a welfare-maximizing airport are used to benchmark and compare the difference with profit-oriented airport decisions, as shown in (2.15)-(2.17). Derivation steps are provided in Appendix B.

Terminal capacity C

Welfare-maximizing airport (benchmark):

$$\underbrace{-q_0 \cdot \frac{\partial c_t}{\partial C}}_{\substack{\text{marginal benefit from}\\ \text{terminal cost reduction}\\ >0}} + \underbrace{\frac{\partial R(q_0, t_s)}{\partial t_s} \cdot \frac{\partial t_s}{\partial C}}_{\substack{\text{marginal concession surplus}\\ \text{from terminal capacity investment}\\ >0}} = \underbrace{\frac{\partial c_{KC}}{\partial C}}_{\substack{\text{marginal cost of terminal}\\ \text{capacity investment}\\ >0}}$$

Profit-maximizing airport:

$$\underbrace{-q_0\cdot\frac{\partial c_t}{\partial C}}_{\substack{\text{marginal benefit from}\\ \text{terminal cost reduction}\\ >0}} + \underbrace{\frac{\partial R(q_0,t_s)}{\partial t_s}\cdot\frac{\partial t_s}{\partial C}}_{\substack{\text{marginal concession surplus}\\ \text{from terminal capacity investment}\\ >0}} = \underbrace{\frac{\partial c_{KC}}{\partial C}}_{\substack{\text{marginal cost of terminal}\\ \text{capacity investment}\\ >0}} + \underbrace{\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial C}}_{\substack{\text{terminal capacity investment}\\ \text{under different volumes}\\ <0 \text{ or } >0}} \tag{2.15}$$

Dwell time in the terminal T

Welfare-maximizing airport (benchmark):

$$\underbrace{\frac{\partial R(q_0,t_s)}{\partial t_s}\cdot\frac{\partial t_s}{\partial T}}_{\substack{\text{marginal concession surplus}\\ \text{from longer terminal time}\\ >0}} = \underbrace{q_0\cdot\frac{\partial c_t}{\partial T}}_{\substack{\text{marginal terminal cost}\\ \text{from longer terminal time}\\ >0}}$$

Profit-maximizing airport:

$$\underbrace{\frac{\partial R(q_0,t_s)}{\partial t_s}\cdot\frac{\partial t_s}{\partial T}}_{\substack{\text{marginal concession surplus}\\ \text{from longer terminal time}\\ >0}} = \underbrace{q_0\cdot\frac{\partial c_t}{\partial T}}_{\substack{\text{marginal terminal cost}\\ \text{from longer terminal time}\\ >0}} + \underbrace{\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial T}}_{\substack{\text{effect of terminal time}\\ \text{under different volume}\\ >0}} \tag{2.16}$$

Runway capacity K

Welfare-maximizing airport (benchmark):

$$\underbrace{-q_0\cdot\frac{\partial c_r}{\partial K}}_{\substack{\text{marginal benefit from}\\ \text{runway delay reduction}\\ >0}} = \underbrace{\frac{\partial c_{KC}}{\partial K}}_{\substack{\text{marginal cost of runway}\\ \text{capacity investment}\\ >0}}$$

Profit-maximizing airport:

$$\underbrace{-q_0\cdot\frac{\partial c_r}{\partial K}}_{\substack{\text{marginal benefit from}\\ \text{runway delay reduction}\\ >0}} = \underbrace{\frac{\partial c_{KC}}{\partial K}}_{\substack{\text{marginal cost of runway}\\ \text{capacity investment}\\ >0}} + \underbrace{\frac{q_0^2}{N}\cdot\frac{\partial^2 c_r}{\partial q_0\partial K}}_{\substack{\text{runway capacity invest}\\ \text{under different volume}\\ <0}} \tag{2.17}$$

As shown in (2.17), comparing the benchmark of a welfare-maximizing airport, the profit-maximizing airport tends to invest more in runway capacity[5], as the marginal benefit of runway expansion is smaller than its marginal cost, which echoes the findings in Kidokoro et al. (2016). In contrast, whether the profit-maximizing airport would overinvest in terminal capacity (as compared to the benchmark) depends on the traffic volumes. As shown in Eq. (2.8), for lower traffic volumes ($q_0 < \bar{\bar{q}}_0$), we have $\frac{\partial}{\partial q_0}\left(\frac{\partial c_t}{\partial C}\right) < 0$. Substituting this result into (2.15), the marginal benefit of terminal capacity expansion is also smaller than its marginal cost, thereby leading to overinvestment. However, for higher traffic volumes ($\bar{\bar{q}}_0 < q_0 < C$), we have $\frac{\partial}{\partial q_0}\left(\frac{\partial c_t}{\partial C}\right) > 0$, thus the marginal benefit is larger than the cost, which leads to underinvestment. Again, this is associated with the diminishing relationship between terminal capacity expansion and travel cost reduction[6]. Regarding the arrival time advised to passengers, the profit-maximizing airport tends to impose an earlier arrival time than the benchmark, for which airline profit loss due to passengers' incremental travel time cost is not incorporated in the profit-oriented airport's decision. Also, passengers' utility loss is not factored into their consideration, therefore a profit-maximizing airport tends to suggest an earlier arrival time to passengers (longer dwell time inside the terminal) to maximize its concession surplus.

[5] Runway capacity expansion lowers the congestion c_r and thus the ticket fare p_0. A lower ticket fare stimulates the trip demand q_0 and increases the concession surplus R, hence profit-oriented airports tend to invest more in runway than the benchmark. Airlines' fare revenue loss due to ticket fare drop is not considered in their objectives.

[6] Similar to runway capacity expansion, under lower traffic volume, the terminal queuing delay is significantly relieved with expansion in terminal capacity, which results in lower air ticket fare and airline's profit loss. While at higher traffic, the effect on queuing delay reduction is less effective, thus the ticket fare drops slower than the induced trip demand and leading to airlines' profit gain. This profit gain is not incorporated into consideration of profit-oriented airports, hence leading to underinvestment in terminal capacity (for higher traffic volumes).

3. Impact of different airport regulations

As shown in Section 2.3.2, by comparison to a welfare-maximizing airport, a profit-maximizing airport tends to advise an earlier arrival time to passengers and invest more in runway capacity and terminal capacity under lower traffic, which deviates from socially optimal outcomes. To restore the outcomes, other than imposing a Pigouvian tax (Czerny et al., 2016), regulators can impose regulatory constraints on airports. In this section, we compare two prevailing regulatory constraints, i.e., single-till and dual-till regulations. Single-till regulation ensures that the total revenue from both aero and non-aero services covers costs, while dual-till regulation leaves non-aero revenue unregulated, covering only aeronautical costs. The concept of airports employing wasteful resources (denoted by μ), borrowed from (Kidokoro and Zhang, 2023b), is used to simplify the derivation of the Lagrangian multiplier of the constrained maximization problems.

3.1. Single-till regulation

Under single-till regulation, regulators maximize the social welfare (net of regulatory waste), subject to the non-positive constraints on airport profit (net of regulatory waste μ), expressed as follows:

$$\max SW - \mu, \qquad s.t.\ \pi_o - \mu \leq 0 \tag{3.1}$$

Then the Lagrangian of the above maximization problem can be expressed as:

$$\Lambda = SW - \mu - \lambda \cdot (\pi_o - \mu) \tag{3.2}$$

where $\lambda \geq 0$ denotes the Lagrangian multiplier. Recalling the definition of social welfare in (2.14) and airport profit in (2.13), the Lagrangian is equivalent to:

$$\Lambda = I - q_0 \cdot (c_t + c_r) - p_1 x_1 + u + R - c_{KC} - \mu - \lambda(q_0 \cdot \tau + R - c_{KC} - \mu) \tag{3.3}$$

Then we derive the first-order conditions w.r.t. airport charge, terminal capacity, terminal time and runway capacity. The detailed derivation steps are shown in Appendix C.

Proposition 1. By comparison with the benchmark (unregulated welfare maximization decisions), the optimal decisions under single-till regulation are characterized by:

a) When the welfare-maximizing charge is less than the profit-maximizing charge, i.e., $\tau_{SW} < \tau_{\pi_o}$, then the charge under single-till regulation is the least of the three charges, i.e., $\tau_{SW}^{sin} < \tau_{SW} < \tau_{\pi_o}$. Otherwise when $\tau_{SW} > \tau_{\pi_o}$, the charge under single-till regulation is the greatest of the three charges, i.e., $\tau_{SW}^{sin} > \tau_{SW} > \tau_{\pi_o}$, as shown in (3.10) and (3.11);

b) Under lower traffic volumes ($q_0 < \bar{\bar{q}}_0$), marginal concession surplus and benefit from terminal capacity expansion is higher than its marginal cost, hence single-till regulation leads to underinvestment in terminal capacity. But under higher traffic volumes ($q_0 > \bar{\bar{q}}_0$), single-till regulation leads to overinvestment, as revealed in (3.5);

c) The marginal concession surplus from a longer terminal time is less than the marginal terminal cost it induces, so single-till regulation leads to a shorter dwell time available for passengers in the terminal (later arrival time suggested to passengers), as revealed in (3.6);

d) The marginal benefit from expanding runway capacity is greater than its marginal cost, hence single-till regulation leads to underinvestment in runway capacity, as shown in (3.7).

$$\tau_{SW}^{\sin} = \underbrace{\frac{\lambda}{1-\lambda} \cdot \frac{q_0}{\frac{\partial q_0}{\partial \tau}}}_{\substack{\text{monopoly} \\ \text{airport charge}}} - \underbrace{\left(\frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0}\right)}_{\substack{\text{concession surplus from} \\ \text{volume and shopping time}}} + \frac{1}{1-\lambda} \cdot \underbrace{q_0 \cdot \frac{\partial \rho_0}{\partial q_0}}_{\substack{\text{marginal} \\ \text{full cost}}} - \frac{1}{1-\lambda} \cdot \underbrace{q_0 \cdot \frac{N-1}{N} \cdot \frac{\partial p_0}{\partial q_0}}_{\substack{\text{marginal profit from} \\ \text{Cournot Competition}}} \tag{3.4}$$

$$\underbrace{-q_0 \cdot \frac{\partial c_t}{\partial C}}_{\substack{\text{marginal benefit from} \\ \text{terminal cost reduction} \\ >0}} + \underbrace{\frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial C}}_{\substack{\text{marginal concession surplus} \\ \text{from capacity investment} \\ >0}} = \underbrace{\frac{\partial c_{KC}}{\partial C}}_{\substack{\text{marginal cost of terminal} \\ \text{capacity investment} \\ >0}} - \underbrace{\frac{\lambda}{1-\lambda} \cdot \frac{q_0^2}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial C}}_{\substack{\text{terminal cost reduction} \\ \text{under different volume} \\ <0 \text{ or } >0}} \tag{3.5}$$

$$\underbrace{\frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial T}}_{\substack{\text{marginal concession surplus} \\ \text{from longer terminal time} \\ >0}} = \underbrace{q_0 \cdot \frac{\partial c_t}{\partial T}}_{\substack{\text{marginal terminal cost} \\ \text{from terminal time} \\ >0}} - \underbrace{\frac{\lambda}{1-\lambda} \cdot \frac{q_0^2}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial T}}_{\substack{\text{effect of terminal time} \\ \text{under different volume} \\ >0}} < q_0 \cdot \frac{\partial c_t}{\partial T} \tag{3.6}$$

$$\underbrace{-q_0 \cdot \frac{\partial c_r}{\partial C}}_{\substack{\text{marginal benefit from} \\ \text{runway delay reduction} \\ >0}} = \underbrace{\frac{\partial c_{KC}}{\partial C}}_{\substack{\text{marginal cost of runway} \\ \text{capacity investment} \\ >0}} - \underbrace{\frac{\lambda}{1-\lambda} \cdot \frac{q_0^2}{N} \cdot \frac{\partial^2 c_r}{\partial q_0 \partial C}}_{\substack{\text{runway capacity invest} \\ \text{under different volume} \\ <0}} > \frac{\partial c_{KC}}{\partial C} \tag{3.7}$$

For readability, derivation of the optimal airport charges for welfare- and profit-maximizing airports under unregulated situations are provided in Appendix B. The optimal charges for welfare-maximizing airport τ_{SW} and profit-maximizing airport τ_{π_o} are derived as follows:

Welfare-maximizing airport:

$$\tau_{SW} = q_0 \cdot \frac{\partial \rho_0}{\partial q_0} - q_0 \cdot \frac{N-1}{N} \cdot \frac{\partial p_0}{\partial q_0} - \left(\frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \right)$$

Profit-maximizing airport:

$$\tau_{\pi_o} = -\frac{q_0}{\frac{\partial q_0}{\partial \tau}} - \left(\frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \right) \tag{3.8}$$

Then the optimal charge under single-till regulation τ_{SW}^{sin} in (3.4) can be expressed as a linear combination of the welfare-maximizing charge τ_{SW} and the profit-maximizing charge τ_{π_o} in (3.8), as follows:

$$\tau_{SW}^{sin} = \frac{-\lambda}{1-\lambda} \cdot \tau_{\pi_o} + \frac{1}{1-\lambda} \cdot \tau_{SW} \tag{3.9}$$

As $0 < \lambda < 1$ (see Appendix C), thus $\frac{-\lambda}{1-\lambda} < 0$, $\frac{1}{1-\lambda} > 0$. If the welfare-maximizing airport charge is less than that of the profit maximizing airport, $\tau_{SW} < \tau_{\pi_o}$ (Basso and Zhang, 2007b; Zhang and Zhang, 2003), then the single-till charge τ_{SW}^{sin} is the least of the three charges, i.e., $\tau_{SW}^{sin} < \tau_{SW} < \tau_{\pi_o}$, as follows:

$$\underbrace{\frac{-\lambda}{1-\lambda} \cdot \tau_{\pi_o} + \frac{1}{1-\lambda} \cdot \tau_{SW}}_{\tau_{SW}^{sin}} < \underbrace{\frac{-\lambda}{1-\lambda} \cdot \tau_{SW} + \frac{1}{1-\lambda} \cdot \tau_{SW}}_{\tau_{SW}} < \underbrace{\frac{-\lambda}{1-\lambda} \cdot \tau_{\pi_o} + \frac{1}{1-\lambda} \cdot \tau_{\pi_o}}_{\tau_{\pi_o}} \tag{3.10}$$

If the welfare-maximizing airport charge is greater than that of a profit maximizing airport, $\tau_{SW} > \tau_{\pi_o}$, then the single-till airport charge τ_{SW}^{sin} is the greatest of the three charges, $\tau_{SW}^{sin} > \tau_{SW} > \tau_{\pi_o}$, as follows:

$$\underbrace{\frac{-\lambda}{1-\lambda} \cdot \tau_{\pi_o} + \frac{1}{1-\lambda} \cdot \tau_{SW}}_{\tau_{SW}^{sin}} > \underbrace{\frac{-\lambda}{1-\lambda} \cdot \tau_{SW} + \frac{1}{1-\lambda} \cdot \tau_{SW}}_{\tau_{SW}} > \underbrace{\frac{-\lambda}{1-\lambda} \cdot \tau_{\pi_o} + \frac{1}{1-\lambda} \cdot \tau_{\pi_o}}_{\tau_{\pi_o}} \tag{3.11}$$

As shown in Proposition 1d), by comparison with the benchmark, single-till regulation leads to a lower runway capacity. Under this regime, the excess concession revenue is taken away and the airport cannot share the benefit from expanding runway capacity. Hence, under single-till regulation, airport operators have fewer incentives to expand runway capacity which is associated with a very high cost. A similar case has been witnessed in urban railways in Tokyo, Japan (Kanemoto and Kiyono, 1995; Kidokoro and Zhang, 2023a), where the regulation of revenue from the side business of railways has hindered investment in railway capacity, thereby leading to overcrowding during rush hours.

Regarding the terminal capacity decisions, under lower traffic volumes, the single-till regulation also results in a lower terminal capacity than the benchmark, as revealed in Proposition 1b). However, under higher traffic volumes, the effect of expanding capacity on reducing travel cost is less pronounced (U-shaped relation). Hence the raised passenger volume from expanding terminal capacity increases queuing time at airport check-in zones, thereby reducing trip demand and concession surplus. The loss of concession surplus is disregarded under single-till regulation, leading to overinvestment in terminal capacity.

Regarding terminal time decisions, the marginal benefit from a longer dwell time in the terminal is less than its marginal cost under single-till regulation. Thus, single-till regulation results in a later arrival time suggested to passengers than the benchmark, for which the excess concession revenue from an earlier arrival time is overlooked under this regulatory regime, as shown in Proposition 1c).

In summary, single-till regulation typically results in lower terminal capacity and dwell time in the terminal as compared with the benchmark (unregulated welfare-maximizing results). Below, we explore how dual-till regulation affects airport operator's decisions on different resources.

3.2. Dual-till regulation

Under dual-till regulation, the airport profit generated from aeronautical services (net of regulatory waste μ) is non-positive, where μ can be regarded as a profit cap, expressed as follows:

$$\underbrace{q_0 \cdot \tau}_{\substack{\text{airport charge}\\ \text{revenue}}} - \underbrace{c_{KC}}_{\substack{\text{variable cost of terminal}\\ \text{and runway investment}}} - \underbrace{F \cdot \alpha_{KC}}_{\substack{\text{fixed cost allocated}\\ \text{to aeronautical services}}} \leq \mu \tag{3.12}$$

where α_{KC} is the proportion of the fixed cost F allocated to aeronautical services.

3.2.1. Dual-till regulation on welfare-maximizing airports

Under dual-till regulation, welfare-maximizing airports aims to maximize the social welfare (net of regulatory waste), subject to the non-positive constraints in (3.12), expressed as follows:

$$\max SW - \mu, \qquad s.t.\ q_0 \cdot \tau - c_{KC} - F \cdot \alpha_{KC} \leq \mu \tag{3.13}$$

Then the Lagrangian of the above maximization problem can be expressed as:

$$\Lambda = SW - \mu - \lambda \cdot (q_0 \cdot \tau - c_{KC} - F \cdot \alpha_{KC} - \mu) \tag{3.14}$$

Replacing the definition of social welfare SW in (2.14), the Lagrangian can be expressed as:

$$\Lambda = I - (c_t + c_r) \cdot q_0 - p_1 \cdot x_1 + u + R - c_{KC} - \mu - \lambda \cdot (\tau \cdot q_0 - c_{KC} - F \cdot \alpha_{KC} - \mu) \tag{3.15}$$

Then we derive the first-order conditions w.r.t. airport charge, terminal capacity, terminal time and runway capacity. The detailed derivation steps are shown in Appendix D.

Proposition 2. Compared to the benchmark and single-till regulation, the optimal decisions made by welfare-maximizing airports under dual-till regulation are characterized by:

a) The optimal charge τ_{SW}^{dual} in (3.16) is less than the optimal charge under single-till τ_{SW}^{sin}, if the positive effect of traffic volume on concession surplus prevails over its negative effect on shopping time and concession surplus, as derived in (3.21);

b) Dual-till regulation results in a higher terminal capacity when compared to single-till regulation. Hence, for lower traffic volumes ($q_0 < \overset{=}{q_0}$), it partially corrects the underinvestment in terminal capacity made by single-till regulation. However, for higher traffic volumes ($q_0 > \overset{=}{q_0}$), it exacerbates the underinvestment, as revealed by (3.17) and (3.22).

c) The dual-till regulation exaggerates the underinvestment in terminal time made by single-till regulation, leading to an even shorter dwell time available for passengers in the terminal (even later arrival time advised to passengers), as revealed by (3.18) and (3.23);

d) The dual-till regulation partially corrects the underinvestment in runway capacity made by single-till regulation, as revealed by (3.19) and (3.24).

$$\tau_{SW}^{dual} = \underbrace{\frac{\lambda}{1-\lambda} \cdot \frac{q_0}{\frac{\partial q_0}{\partial \tau}}}_{\substack{\text{monopoly}\\ \text{airport charge}}} + \frac{1}{1-\lambda} \cdot \underbrace{\left(q_0 \cdot \frac{\partial \rho_0}{\partial q_0} - q_0 \cdot \frac{N-1}{N} \cdot \frac{\partial p_0}{\partial q_0} \right)}_{\substack{\text{excess profit from}\\ \text{Cournot competition}}} - \frac{1}{1-\lambda} \cdot \underbrace{\left(\frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \right)}_{\substack{\text{concession surplus from traffic}\\ \text{volume and shopping time}}} \tag{3.16}$$

$$\underbrace{-q_0 \cdot \frac{\partial c_t}{\partial C}}_{\substack{\text{marginal benefit of}\\ \text{terminal cost drop}\\ >0}} + \frac{1}{1-\lambda} \cdot \underbrace{\frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial C}}_{\substack{\text{marginal concession surplus}\\ \text{from capacity investment}\\ >0}} = \underbrace{\frac{\partial c_{KC}}{\partial C}}_{\substack{\text{marginal cost of}\\ \text{capacity investment}\\ >0}} - \frac{\lambda}{1-\lambda} \cdot \underbrace{\frac{q_0^2}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial C}}_{\substack{\text{terminal cost}\\ \text{reduction}\\ <0 \text{ or } >0}} - \frac{\lambda}{1-\lambda} \cdot F \cdot \underbrace{\frac{\partial \alpha_{KC}}{\partial C}}_{\substack{\text{aeronautical}\\ \text{cost}\\ >0}} \tag{3.17}$$

$$\underbrace{\frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial T}}_{\substack{\text{marginal shop rental}\\ \text{from longer terminal time}\\ >0}} = (1-\lambda) \cdot \underbrace{q_0 \cdot \frac{\partial c_t}{\partial T}}_{\substack{\text{marginal terminal}\\ \text{cost from terminal time}\\ >0}} - (1-\lambda) \cdot \underbrace{\frac{\lambda}{1-\lambda} \cdot \frac{q_0^2}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial T}}_{\substack{\text{effect of terminal time}\\ \text{under different volume}\\ >0}} \tag{3.18}$$

$$\underbrace{-q_0 \cdot \frac{\partial c_r}{\partial K}}_{\substack{\text{marginal benefit from}\\ \text{runway delay reduction}\\ >0}} = \underbrace{\frac{\partial c_{KC}}{\partial K}}_{\substack{\text{marginal cost of runway}\\ \text{capacity investment}\\ >0}} \quad \frac{\lambda}{1-\lambda} \cdot \underbrace{\frac{q_0^2}{N} \cdot \frac{\partial^2 c_r}{\partial q_0 \partial K}}_{\substack{\text{runway cost}\\ \text{saving}\\ <0}} - \frac{\lambda}{1-\lambda} \cdot F \cdot \underbrace{\frac{\partial \alpha_{KC}}{\partial K}}_{\substack{\text{aeronautical}\\ \text{cost}\\ >0}} \tag{3.19}$$

Comparing welfare-maximizing charges under single-till and dual-till regulations, their difference depends on the trade-off between the positive effect of traffic volume on concession surplus and the negative effect of traffic volume on the shopping time and concession surplus, expressed as follows:

$$\tau_{SW}^{dual} - \tau_{SW}^{sin} = \underbrace{-\frac{\lambda}{1-\lambda}}_{<0} \cdot \left(\underbrace{\frac{\partial R}{\partial q_0}}_{>0} + \underbrace{\frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0}}_{<0} \right) \tag{3.20}$$

Hence, dual-till regulation leads to a lower airport charge than single-till regulation if the traffic volume increases the concession surplus, which is prevalent in most commercial airports. Otherwise, if higher traffic reduces the concession surplus, the dual-till regulation charges a higher price, as follows:

$$\tau_{SW}^{dual} < \tau_{SW}^{sin} \text{ if } \underbrace{\frac{\partial R}{\partial q_0}}_{\substack{\text{concession surplus gain} \\ \text{from traffic volume increase} \\ >0}} > \underbrace{-\frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0}}_{\substack{\text{concession surplus loss} \\ \text{from shopping time shrinkage} \\ <0}} \text{, otherwise } \tau_{SW}^{dual} > \tau_{SW}^{sin} \tag{3.21}$$

Rearranging the FOC in (3.17), under dual-till regulation, the marginal concession surplus and benefit from terminal capacity expansion is less than that under single-till regulation, expressed as follows:

$$-q_0 \frac{\partial c_t}{\partial C} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial C} = \underbrace{\underbrace{\underbrace{\frac{\partial c_{KC}}{\partial C}}_{\substack{\text{marginal benefit} \\ \text{under \textbf{benchmark}}}} + \underbrace{\frac{-\lambda}{1-\lambda} \cdot \frac{q_0^2}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial C}}_{\substack{\text{effect of terminal capacity} \\ \text{on cost reduction}}}}_{\text{marginal benefit under \textbf{single-till regulation}}} + \underbrace{\frac{-\lambda}{1-\lambda} \cdot \left(\underbrace{F \cdot \frac{\partial \alpha_{KC}}{\partial C}}_{\substack{\text{fixed cost} \\ \text{allocated } >0}} + \underbrace{\frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial C}}_{\substack{\text{marginal concession} \\ \text{surplus } >0}} \right)}_{<0}}_{\text{marginal benefit under \textbf{dual-till regulation}}} \tag{3.22}$$

In comparison with the benchmark, whether dual-till regulation leads to over- or under-investment in terminal capacity is contingent upon traffic volumes. With lower traffic volumes, where single-till regulation results in underinvestment, dual-till regulation can partially correct the distortion made by single-till regulation, $C_{SW}^{dual} > C_{SW}^{sin}$. While for higher traffic volumes, where single-till regulation results in overinvestment in capacity, dual-till regulation exaggerates the distortion, $C_{SW}^{dual} > C_{SW}^{sin} > C_{SW}$.

Rearranging the FOC in (3.18), under dual-till regulation, the marginal benefit of extending passengers' dwell time inside the terminal is less than that under single-till regulation, expressed as follows:

$$\frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial T} = (1-\lambda) \left(\underbrace{q_0 \frac{\partial c_t}{\partial T} + \underbrace{\frac{-\lambda}{1-\lambda}}_{<0} \cdot \underbrace{\frac{q_0^2}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial T}}_{<0}}_{\substack{\text{marginal concession surplus} \\ \text{under \textbf{dual-till regulation}}}} \right) < \underbrace{q_0 \frac{\partial c_t}{\partial T} + \underbrace{\frac{-\lambda}{1-\lambda}}_{<0} \cdot \underbrace{\frac{q_0^2}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial T}}_{>0}}_{\substack{\text{marginal concession surplus} \\ \text{under \textbf{single-till regulation}}}} < \underbrace{q_0 \frac{\partial c_t}{\partial T}}_{\substack{\text{marginal concession surplus} \\ \text{under \textbf{benchmark}}}} \tag{3.23}$$

Although a shorter dwell time inside the airport terminal reduces concession surplus, it saves the travel time cost for passengers. As dual-till regulation only ensures that the revenue from aero services can cover its cost, thus it values passengers' travel cost reduction over concession surplus loss. Consequently, dual-till regulation results in an even shorter dwell time in the airport terminal as compared with the single-till regulation, i.e., $T_{SW}^{dual} < T_{SW}^{sin} < T_{SW}$.

Rearranging the FOC in (3.19), under dual-till regulation, the marginal benefit of expanding runway capacity is less than that under single-till regulation, expressed as follows:

$$-q_0 \cdot \frac{\partial c_r}{\partial C} = \underbrace{\underbrace{\underbrace{\frac{\partial c_{KC}}{\partial C}}_{\substack{\text{marginal benefit} \\ \text{under \textbf{benchmark}}}} + \underbrace{\underbrace{\frac{-\lambda}{1-\lambda}}_{<0} \cdot \underbrace{\frac{q_0^2}{N} \cdot \frac{\partial^2 c_r}{\partial q_0 \partial C}}_{\text{cost reduction } <0}}_{>0}}_{\text{marginal benefit under \textbf{single-till regulation}}} + \underbrace{\underbrace{\frac{-\lambda}{1-\lambda}}_{<0} \cdot \underbrace{F \cdot \frac{\partial \alpha_{KC}}{\partial C}}_{\text{fixed cost } >0}}_{<0}}_{\text{marginal benefit under \textbf{duall-till regulation}}} \tag{3.24}$$

Hence, dual-till regulation partially corrects the underinvestment in runway capacity made by single-till regulation, i.e., $K_{SW}^{dual} > K_{SW}^{sin}$. However, whether dual-till regulation can restore the outcomes under unregulated welfare maximization (benchmark) depends on the trade-off between the effect of capacity expansion on reducing runway delays and the fixed cost allocated to aeronautical services, as the former effect leads to underinvestment, but the latter leads to overinvestment. The former effect prevails over the latter under perfect competition, which is consistent with Kidokoro et al. (2016).

In summary, the imposition of dual-till regulation partially rectifies the distortions introduced by single-till regulation in both runway and terminal capacity decisions. However, it exacerbates the distortion in terminal time decisions, thereby failing to provide a superior alternative to single-till regulation.

3.2.2. Comparison between dual-till and single-till regulations on welfare-maximizing airports

In this section, we further examine the resulting social welfare under both single-till and dual-till regimes. For welfare-maximizing airports, the difference arises from whether non-aeronautical services profit is incorporated into the constraint. The two constraints can be integrated into a linear combination, $q_0 \cdot \tau - c_{KC} - F \cdot \alpha_{KC} + \beta(R - F\cdot(1-\alpha_{KC})) \leq \mu$. Then, $\beta = 0$ and $\beta = 1$ refers to dual-till and single-till regulation. The results are like that in Kidokoro et al. (2016), i.e., $\frac{\partial SW}{\partial \beta} < 0$ if $R > F \cdot (1-\alpha_{KC})$. We omit the proof here. When the concession surplus is positive, dual-till regulation results in higher social welfare as it adjusts the decisions in time and capacity to ensure the financial viability of aeronautical services. Compared to single-till regulation, dual-till regulation tends to attract more passengers to the airport by reducing the terminal and runway delay costs. As demonstrated in Proposition 2, if concession surplus is making profit, dual-till regulation leads to a lower airport charge, lower terminal time, and higher terminal and runway capacity. The increased ridership of the airport, coupled with their enhanced utility, boosts overall social welfare. Therefore, we offer an alternative explanation to the explanation provided by Kidokoro et al. (2016) and Kidokoro and Zhang (2018), where the unregulated profit from non-aeronautical services under dual-till regulation increases social welfare. We posit that dual-till's superiority over single-till regulation in terms of social welfare can also be attributed to the resulting higher passenger volume and increased consumer utility. Below, we examine whether the dual-till regulation on profit-maximizing airports can restore the welfare-maximizing outcomes.

3.2.3. Dual-till regulation on profit-maximizing airports

Under dual-till regulation, the airport authority aims to maximize its profit (net of regulatory waste), and its decisions are subject to the non-positive constraints in (3.12), expressed as follows:

$$\max \ \pi_o - \mu, \qquad s.t. \ q_0 \cdot \tau - c_{KC} - F \cdot \alpha_{KC} \leq \mu \tag{3.25}$$

Then the Lagrangian of the above maximization problem can be expressed as:

$$\Lambda = \pi_o - \mu - \lambda(q_0 \cdot \tau - c_{KC} - F \cdot \alpha_{KC} - \mu) \tag{3.26}$$

Further replacing π_o with the definition of airport profit in (2.13), the Lagrangian can be expressed as:

$$\Lambda = \tau \cdot q_0 + R - c_{KC} - \mu - \lambda(\tau \cdot q_0 - c_{KC} - F \cdot \alpha_{KC} - \mu) \tag{3.27}$$

Then we derive the first-order conditions w.r.t. airport charge, terminal capacity, terminal time and runway capacity. Detailed derivation steps are shown in Appendix E.

Proposition 3. Compared to the benchmark and profit maximization case, the optimal decisions made by profit-maximizing airports under dual-till regulation are characterized by:

a) The optimal charge $\tau_{\pi_o}^{dual}$ in (3.28) is less than the charge under an unregulated case τ_{π_o}, if the positive effect of traffic volume on concession surplus value prevails over its negative effect on shopping time and concession surplus, as derived in (3.32);

b) Dual-till regulation results in higher terminal capacity than the profit maximization case. Hence for lower traffic volumes ($q_0 < \bar{q}_0$), it exaggerates the underinvestment in terminal capacity made by profit maximization. But for higher traffic volumes ($q_0 > \bar{q}_0$), it partially corrects the overinvestment, as shown in (3.29) and (3.33);

c) Dual-till regulation partially rectifies the overinvestment in terminal time caused by profit-maximizing decisions (a later arrival time advised to passengers as compared to unregulated profit-maximization case), as revealed in (3.30) and (3.34);

d) Dual-till regulation exacerbates the overinvestment in runway capacity caused by profit maximization, thereby resulting in even higher runway capacity, as shown in (3.31) and (3.35).

$$\tau_{\pi_o}^{dual} = \underbrace{-\frac{q_0}{\frac{\partial q_0}{\partial \tau}}}_{\substack{\text{monopoly} \\ \text{airport charge}}} - \frac{1}{1-\lambda} \cdot \underbrace{\left(\frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0}\right)}_{\substack{\text{concession surplus from traffic volume} \\ \text{increase and shopping time shrinkage}}} \tag{3.28}$$

$$\underbrace{-q_0 \cdot \frac{\partial c_t}{\partial C}}_{\substack{\text{marginal benefit of} \\ \text{terminal cost drop} \\ >0}} + \frac{1}{1-\lambda} \cdot \underbrace{\frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial C}}_{\substack{\text{marginal concession surplus} \\ \text{from capacity investment} \\ >0}} = \underbrace{\frac{\partial c_{KC}}{\partial C}}_{\substack{\text{marginal cost of} \\ \text{capacity investment} \\ >0}} + \underbrace{\frac{q_0^2}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial C}}_{\substack{\text{terminal cost} \\ \text{reduction} \\ <0 \text{ or } >0}} - \frac{\lambda}{1-\lambda} \cdot \underbrace{F \cdot \frac{\partial \alpha_{KC}}{\partial C}}_{\substack{\text{aeronautical} \\ \text{cost} \\ >0}} \tag{3.29}$$

$$\underbrace{\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial T}}_{\substack{\text{marginal shop rental}\\ \text{from longer terminal time}\\ >0}} = (1-\lambda)\cdot\underbrace{q_0\cdot\frac{\partial c_t}{\partial T}}_{\substack{\text{marginal terminal}\\ \text{cost from terminal time}\\ >0}} + (1-\lambda)\cdot\underbrace{\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0 \partial T}}_{\substack{\text{terminal cost}\\ \text{reduction}\\ >0}} \tag{3.30}$$

$$\underbrace{-q_0\cdot\frac{\partial c_r}{\partial K}}_{\substack{\text{marginal benefit from}\\ \text{runway delay reduction}\\ >0}} = \underbrace{\frac{\partial c_{KC}}{\partial K}}_{\substack{\text{marginal cost of runway}\\ \text{capacity investment}\\ >0}} + \underbrace{\frac{q_0^2}{N}\cdot\frac{\partial^2 c_r}{\partial q_0 \partial K}}_{\substack{\text{runway cost}\\ \text{saving}\\ <0}} - \frac{\lambda}{1-\lambda}\cdot\underbrace{F\cdot\frac{\partial \alpha_{KC}}{\partial K}}_{\substack{\text{aeronautical}\\ \text{cost}\\ >0}} \tag{3.31}$$

From (3.28) and (3.8), an interesting coincidence is that the difference in airport charges determined by regulated (dual-till) and unregulated profit-maximizing airports is the same as the difference in airport charge determined by single-till and dual-till welfare-maximizing airports in (3.20), as follows:

$$\tau_{\pi_o}^{dual} - \tau_{\pi_o} = \underbrace{-\frac{\lambda}{1-\lambda}}_{<0}\cdot\left(\underbrace{\frac{\partial R}{\partial q_0}}_{>0} + \underbrace{\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial q_0}}_{<0}\right) = \tau_{SW}^{dual} - \tau_{SW}^{sin} \tag{3.32}$$

Hence, when a high traffic volume increases the concession surplus, thereby offsetting its negative impact on shopping time, the imposition of dual-till regulation on profit-maximizing airports will lower the airport charge. Otherwise, dual-till regulation increases the charge to fulfill the constraints where the revenue generated from aeronautical services is sufficient to cover costs.

Rearranging the FOC in (3.29), the marginal concession surplus and benefit of terminal capacity expansion under dual-till regulation is less than that in the unregulated case, expressed as follows:

$$-q_0\cdot\frac{\partial c_t}{\partial C} + \frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C} = \underbrace{\underbrace{\underbrace{\frac{\partial c_{KC}}{\partial C}}_{\substack{\text{marginal benefit}\\ \text{under } \textbf{benchmark}}} + \underbrace{\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0 \partial C}}_{\substack{\text{effect of terminal}\\ \text{capacity on cost reduction}}}}_{\text{marginal benefit for } \textbf{profit} \text{ max. } \textbf{airport}} + \underbrace{\frac{-\lambda}{1-\lambda}\cdot\left(\underbrace{F\cdot\frac{\partial \alpha_{KC}}{\partial C}}_{\substack{\text{fixed cost}\\ >0}} + \underbrace{\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C}}_{\substack{\text{marginal concession}\\ \text{surplus } >0}}\right)}_{<0}}_{\text{marginal benefit for } \textbf{profit} \text{ max. } \textbf{airport} \text{ under } \textbf{dual-till regulation}} \tag{3.33}$$

Hence, compared to the profit-maximization case, dual-till regulation leads to overinvestment in terminal capacity. As shown in Proposition 3b), whether dual-till regulation can correct the distortion made by profit-maximizing decisions depends on the trade-off between the effect of terminal expansion on terminal cost reduction, fixed cost allocated to aeronautical services and shop rental. For lower traffic volumes, where terminal capacity expansion reduces the terminal cost efficiently, dual-till regulation exaggerates overinvestment in terminal capacity, i.e., $C_{\pi_o}^{dual} > C_{\pi_o} > C_{SW}$. For higher traffic volumes, dual-till regulation partially rectifies the underinvestment, i.e., $C_{\pi_o}^{dual} > C_{\pi_o} < C_{SW}$.

Rearranging the FOC in (3.30), the marginal concession surplus from a longer terminal time under dual-till regulation is less than that under the unregulated case, expressed as follows:

$$\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial T} = \underbrace{(1-\lambda)\cdot\left(q_0\cdot\frac{\partial c_t}{\partial T} + \underbrace{\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0 \partial T}}_{>0}\right)}_{\substack{\text{marginal concession surplus under } \textbf{\textit{dual}}\\ \textbf{\textit{-till}} \text{ regulation on } \textbf{\textit{profit-max}}. \text{ airports}}} < \underbrace{\left(q_0\cdot\frac{\partial c_t}{\partial T} + \underbrace{\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0 \partial T}}_{>0}\right)}_{\substack{\text{marginal concession surplus on}\\ \textbf{\textit{profit-max}}. \text{ airports}}} > \underbrace{q_0\cdot\frac{\partial c_t}{\partial T}}_{\substack{\text{marginal concession}\\ \text{surplus on } \textbf{\textit{welfare-max}}.\\ \text{airports } (\textbf{\textit{benchmark}})}} \tag{3.34}$$

Given that an extended terminal time increases terminal costs and reduces revenue from aeronautical services, regulators imposing dual-till regulation are likely to reduce dwell time in the terminal to increase aeronautical revenue to cover the cost. Thus, dual-till regulation partially rectifies the distortion in terminal time decision in the case of unregulated profit maximization, i.e., $T_{\pi_o}^{dual} < T_{\pi_o} > T_{SW}$.

Rearranging the FOC in (3.31), the marginal benefit of runway investment under dual-till regulation is less than that in the unregulated case and benchmark, as follows:

$$-q_0\cdot\frac{\partial c_r}{\partial K}=\underbrace{\frac{\partial c_{KC}}{\partial K}+\underbrace{\frac{q_0^2}{N}\cdot\frac{\partial^2 c_r}{\partial q_0\partial K}}_{<0}+\underbrace{\frac{-\lambda\cdot F}{1-\lambda}\cdot\frac{\partial \alpha_{KC}}{\partial K}}_{<0}}_{\text{marginal benefit under } \textbf{\textit{dual-till}} \text{ regulation on } \textbf{\textit{profit-maximizing}} \text{ airports}}<\underbrace{\frac{\partial c_{KC}}{\partial K}+\underbrace{\frac{q_0^2}{N}\cdot\frac{\partial^2 c_r}{\partial q_0\partial K}}_{<0}}_{\text{marginal benefit on } \textbf{\textit{profit-maximizing}} \text{ airports}}<\underbrace{\frac{\partial c_{KC}}{\partial K}}_{\text{marginal benefit on } \textbf{\textit{welfare-maximizing}} \text{ airports } (\textbf{\textit{benchmark}})} \tag{3.35}$$

Hence, dual-till regulation imposed on profit-maximizing airports fails to rectify the overinvestment in runway capacity. It turns out to exacerbate the overinvestment in runway capacity as regulators need to generate sufficient aeronautical revenue to cover costs, particularly the fixed cost allocated to the aeronautical services. In other words, overinvestment in runway capacity reduces runway delay and increases traffic volume, thereby fulfilling the constraint of dual-till regulation.

The decisions on airport charge, terminal capacity, terminal time and runway capacity with various objectives (profit- or welfare-maximizing) and under regulatory constraints (single-till, dual-till) are summarized in Table 1. To facilitate the comparison of airport decisions under different regimes, the optimal airport charges are revealed in Fig. 2, and the optimal terminal time, terminal and runway capacity are shown in Fig. 3. Here we use yellow dots to indicate the decisions made by welfare-maximizing airports in the unregulated case (benchmark), red dots to indicate the decisions made under single-till regulation and blue dots to denote the decisions under profit-maximization.

It is worth noting that there exists a possibility where the optimal terminal capacity derived from different regulatory regimes may exceed the optimal runway capacity. Under such situations, passengers would experience very short terminal delays but rather a longer runway delay. As such, the runway delay might either propagate back to the terminal (allowing a longer dwell time for passengers and hence a higher chance of purchasing airport goods) or increase passengers' runway delay costs. While such scenarios rarely happen in practice, as most of the terminal expansion projects are led by the runway capacity expansion for most of the international hubs (as passenger demand is capacitated by the runway capacity, not the terminal capacity in general).

As shown Fig. 2, single-till and profit-maximization distort the airport charge in two opposite directions. Similarly, as shown in Fig. 3, they distort the decisions on terminal capacity, terminal time, and runway capacity in opposite directions. For a lower traffic volume, single-till regulation leads to underinvestment in three types of resources while profit-maximizing decisions lead to overinvestment in these resources. For dual-till regulations imposed on welfare-maximizing airports, although it exacerbates the distortion in terminal time decisions caused by single-till regulation, it corrects the distortion in terminal and runway capacity under a lower traffic volume. Similar situations are observed for dual-till regulation imposed on profit-maximizing airports. In a nutshell, the dual-till regulation worsens the distortion made by profit-maximization or single-till regulation in some resources but also corrects the distortion in other types of resources. Therefore, no regulatory constraints (single-till or dual-till) can restore the unregulated welfare maximizing results in all types of resources.

Table 1
Summary of airport decisions on charge, terminal capacity, terminal time, and runway capacity.

Regimes	Airport charge	Terminal capacity	Terminal time	Runway capacity
Single-till Social welfare Maximization	If the profit-maximizing charge is higher than the social welfare maximizing charge, i.e., $\tau_{SW}<\tau_{\pi_o}$, then single-till reduces the airport charge, i.e., $\tau_{SW}^{sin}<\tau_{SW}<\tau_{\pi_o}$.	Underinvestment under lower traffic volumes $C_{SW}^{sin}<C_{SW}$ if $q_0<\bar{\bar{q}}_0$ [c] Overinvestment under higher traffic volumes $C_{SW}^{sin}>C_{SW}$ if $q_0>\bar{\bar{q}}_0$ [c]	Shorter terminal time $T_{SW}^{sin}<T_{SW}$	Underinvestment $K_{SW}^{sin}<K_{SW}$
Dual-till Social welfare Maximization	Lower than the single-till regulation if higher traffic volume increases the concession surplus [d].	Corrects the underinvestment [a] under lower traffic volumes [c], $C_{SW}^{dual}>C_{SW}^{sin}<C_{SW}$ Exaggerates the overinvestment [a] of under higher traffic volumes [c], $C_{SW}^{dual}>C_{SW}^{sin}>C_{SW}$	Exaggerates the underinvestment [a] in terminal time. $T_{SW}^{dual}<T_{SW}^{sin}<T_{SW}$	Corrects the underinvestment [a]. $K_{SW}^{dual}>K_{SW}^{sin}<K_{SW}$
Dual-till Airport profit Maximization	Lower than the unregulated profit maximization case if higher traffic volume increases the concession surplus [d].	Exaggerates the overinvestment [b] under lower traffic volumes [c], $C_{\pi_o}^{dual}>C_{\pi_o}>C_{SW}$ Corrects the underinvestment [b] under higher traffic volumes [c], $C_{\pi_o}^{dual}>C_{\pi_o}<C_{SW}$	Corrects the overinvestment [b] in terminal time. $T_{\pi_o}^{dual}<T_{\pi_o}>T_{SW}$	Exaggerates the overinvestment [b]. $K_{\pi_o}^{dual}>K_{\pi_o}>K_{SW}$

[a] Here the distortion refers to the case under single-till welfare maximization as compared to the benchmark (welfare maximization).
[b] Here the distortion refers to the case under unregulated airport profit maximization as compared to the benchmark (welfare maximization).
[c] Here the critical traffic volume $\bar{\bar{q}}_0$ corresponds to the case where $\frac{\partial^2 c_t}{\partial q_0\partial K}=0$, the expression is given in Eqs. (2.8).
[d] The conclusion holds when the increase of concession surplus from volume prevails over the shrinkage due to shopping time loss, $\frac{\partial R}{\partial q_0}>-\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial q_0}$.

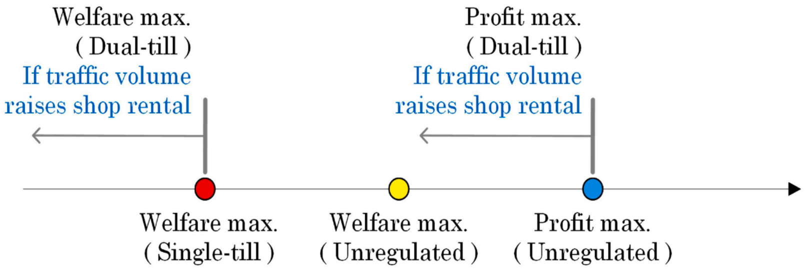

Fig. 2. Optimal airport charge under different regulatory regimes if the profit-maximizing charge is greater than the welfare-maximizing charge.

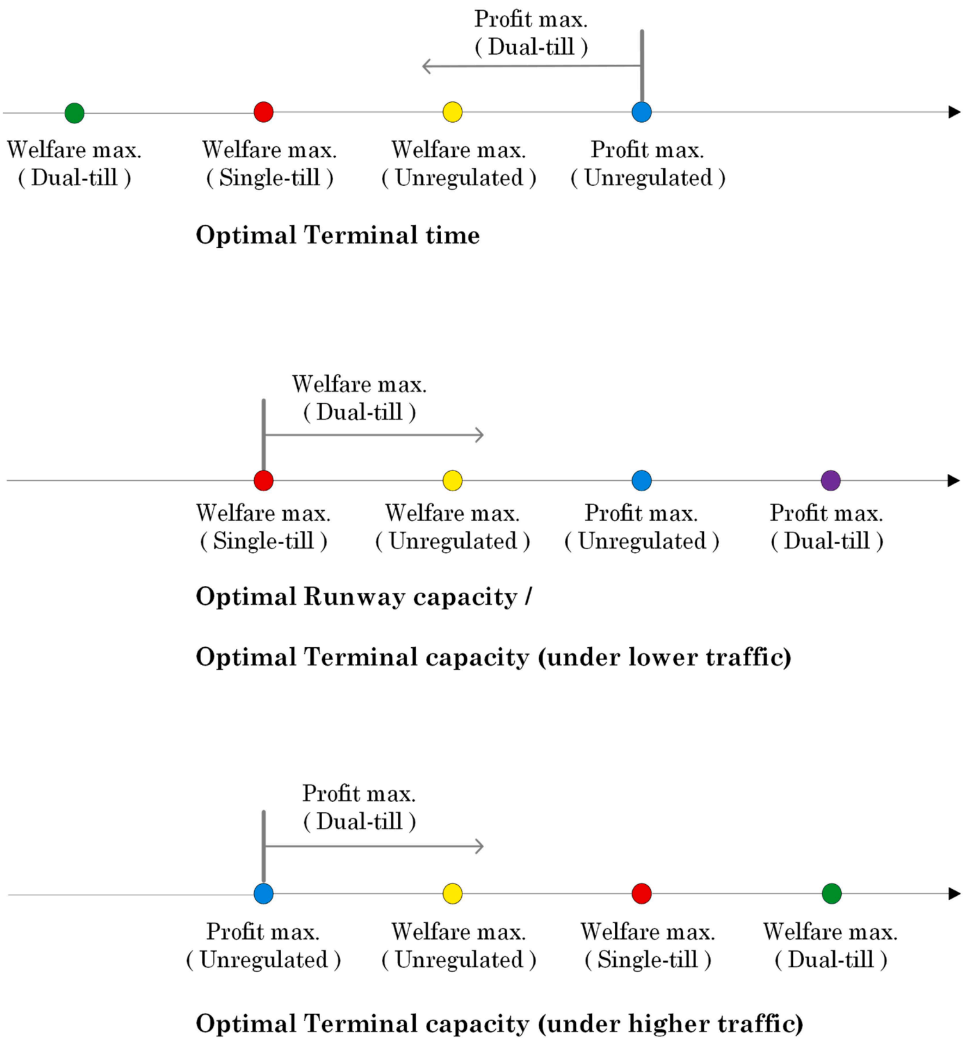

Fig. 3. Optimal decisions for capacity (runway and terminal) and terminal time made by welfare- and profit-maximizing airports under different regulatory regimes (not to scale, for illustration).

4. Concluding remarks and extensions

In this study, we have modeled the interactions between air passengers, airlines, and an airport that runs both aero and non-aero services in a subgame perfect Nash equilibrium. Under different regulatory constraints (single- or dual-till), we explored the airport's strategic decisions regarding charge, advised arrival time to passengers, terminal capacity and runway capacity. By integrating the non-linear relationship between queuing time in the check-in zone and shopping time in the retail zone, we discovered the volume-dependent terminal capacity decisions under various regulatory constraints, which have been overlooked in existing non-aeronautical studies.

A key distinction from the existing literature is that the effect of shopping time on concession revenue has been analyzed under both single-till and dual-till regulations. The unique diminishing relation between terminal capacity and shopping time alters the terminal capacity decisions under higher traffic volume. As compared to single-till regulation, dual-till regulation tends to increase the ridership of the airport by lowering the travel time cost for passengers. Hence, it results in a lower charge, a shorter dwell time inside the terminal (a later arrival time advised to passengers), and a higher runway and terminal capacity to reduce the queuing delay incurred in the terminal and runway, which allows a longer shopping time for passengers to relieve the stress level derived from the queuing and hassles in the check-in zone. This highlights the significance of factoring in passengers' shopping time in analyzing airport reactions to different regulatory constraints, which makes this work among the pioneers in non-aeronautical studies.

Another interesting finding is that single-till regulation on profit-maximizing airports distorts airport decisions in two opposite directions. By and large, profit-maximizing airports tend to overinvest in most of the resources, e.g., advising passengers to have an earlier arrival time at the airport (for a longer dwell time in the terminal), and higher runway and terminal capacities. In contrast, single-till regulation leads to underinvest in these resources, e.g., shorter dwell time in the terminal and lower capacities. This mirrors the railway regulation outcomes in Tokyo and Hong Kong. The revenue cap regulation (similar to the single-till regulation) enacted in Tokyo urban railway hinders the development of railway infrastructure and service upgrade, for which the excess profit from side business is regulated and the railway company lacks incentive to improve the service quality. Consequently, overcrowding is observed during rush hours (Kidokoro and Zhang, 2023a). As for Hong Kong, sizable land parcels are granted to the railway company for property development to cover the railway construction cost, which also allows the cross-subsidization between railway operation ("aero services") and housing development ("non-aero services"). This initiates a positive cycle where the enhanced service frequency and quality are capitalized into the property value, which motivates the railway company to further upgrade the services (Huai et al., 2021; Ma and Lo, 2013; Ng and Lo, 2017). As a result, the operation reaches a 99.96% on-time performance and earns enough ticket revenue to cover its operating cost, which is among the first public transit services to operate without the need for government subsidies. However, the exorbitant property prices near rail stations make private housing less affordable to buyers, which also raises concerns that unregulated profit-maximizing airports might price out some passengers for concession goods and other non-aeronautical services.

It is worth noting that apart from terminal capacity and advised arrival time to passengers, some other factors may also affect passengers' shopping behavior and hence the shop rental and concession revenue. For instance, the baggage allowance (Jiang and Zheng, 2020), the layout of the airport terminal (Hsu and Chao, 2005), the boarding gate allocation to different carriers and the portfolio of convenience and luxury stores affect the chance of airport goods purchasing and concession revenue. Also, air passengers may have multiple airports for departure, hence the airport competition can also affect airport decisions under different regulatory constraints. To tackle these issues, a more detailed modeling effort supported by empirical evidence is needed in the future. Besides, for analytical tractability, the pricing of various non-aeronautical supplies (e.g., car parking, food and beverage, luxury goods) is assumed to be exogenously given in this study. In a more realistic situation, the price of airport goods might play a more significant role in airport concession revenue. For example, airports may lower the price for some airport goods as the loss leader (e.g., providing shopping discounts for duty-free luxury goods), which incentivizes passengers to purchase other airport goods with a higher profit margin and attracts passengers from other airports in a multi-airport region. Under that situation, even with a short available time for shopping, passengers would still be willing to visit the retail shops (Zheng et al., 2025). Consequently, endogenizing the decisions on pricing of airport goods under different regulatory regimes can well capture the intricate relationship between passengers' shopping behavior, airport operations and pricing strategies under airport competition. Also, incorporating the sequential relationships between terminal delay and runway delay would be an interesting topic to be further explored in the future. Finally, once more detailed data is available (e.g., shop rental of different concessionaries, passenger flow of airport shops, profitability profiles), numerical simulations and sensitivity analyses can be conducted to calibrate the parameters, ensuring that those optimal decisions are feasible (e.g., average arrival time, capacity decisions), and to provide further insights of the impacts of various regulatory regimes. The calibration and simulation, though out of the scope of the present paper, is a natural extension of the present research.

CRediT authorship contribution statement

Yue Huai: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Enoch Lee:** Writing – review & editing, Validation, Investigation, Conceptualization. **Hong K. Lo:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Anming Zhang:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

None

Acknowledgements

The authors are grateful to the three anonymous referees and Associate Editor Prof. Robin Lindsey for their constructive comments and suggestions that led to a significant improvement of the paper. We greatly appreciate the helpful comments and discussions with Jan Brueckner, Achim Czerny, Xiaowen Fu, Zhi-Chun Li, Yulai (Sarah) Wan, Changmin Jiang, Hangjun Yang, Kun Wang, Wenyi Xia, Chunan Wang, Wei Liu and the seminar participants of 2023 International Aviation Technology and Business Conference (Hong Kong), 1st ATRS World Conference China Chapter (Beijing), 2024 Conference of International Transportation Economics Association ITEA (Leeds), the 27th ATRS World Conference (Lisbon), and 28th international conference of Hong Kong Society for Transportation Studies (HKSTS). We gratefully acknowledge the Airport Authority of Hong Kong for their data and discussion. We thank the financial support from Research Grants Council (No. 16207920, No. 16212222) of Hong Kong SAR Government, Social Science and Humanities Research Council of Canada (No. 410-2011-0569, No. 435-2019-0525), and National Natural Science Foundation of China (No. 71890974, No. 71890970). All remaining errors are our own.

Appendix A. Total differentiation of trip cost and price of good

Total differentiating the trip cost ρ_0 defined in (2.2), we have:

$$d\rho_0 = \frac{\partial^2 u}{\partial q_0^2}\cdot dq_0 + \frac{\partial^2 u}{\partial q_0 \partial x_1}\cdot dx_1 \tag{A.1}$$

From (2.10), the trip cost can be expressed as: $\rho_0 = \tau - \frac{q_0}{N}\cdot\left(\frac{\partial^2 u}{\partial q_0^2} - \frac{\partial c_t}{\partial q_0} - \frac{\partial c_r}{\partial q_0}\right) + c_t + c_r$, which is a function of terminal capacity C, dwell time at terminal T, runway capacity K, demand of good x_1 and airport charge τ. Total differentiating the trip cost ρ_0 from the above expression, we have:

$$d\rho_0 = \frac{\partial \rho_0}{\partial q_0}\cdot dq_0 + \frac{\partial \rho_0}{\partial \tau}\cdot d\tau + \frac{\partial \rho_0}{\partial K}\cdot dK + \frac{\partial \rho_0}{\partial T}\cdot dT + \frac{\partial \rho_0}{\partial C}\cdot dC + \frac{\partial \rho_0}{\partial x_1}\cdot dx_1 \tag{A.2}$$

Then the first-order derivative of trip cost ρ_0 w.r.t. trip demand q_0 can be expressed as:

$$\begin{aligned}\frac{\partial \rho_0}{\partial q_0} &= -\frac{1}{N}\cdot\left(\frac{\partial^2 u}{\partial q_0^2} - \frac{\partial c_t}{\partial q_0} - \frac{\partial c_r}{\partial q_0}\right) - \frac{q_0}{N}\cdot\left(\frac{\partial^3 u}{\partial q_0^3} - \frac{\partial^2 c_t}{\partial q_0^2} - \frac{\partial^2 c_r}{\partial q_0^2}\right) + \frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0}\\ &= -\frac{1}{N}\cdot\left(\frac{\partial^2 u}{\partial q_0^2}\right) - \frac{q_0}{N}\cdot\left(\frac{\partial^3 u}{\partial q_0^3} - \frac{\partial^2 c_t}{\partial q_0^2} - \frac{\partial^2 c_r}{\partial q_0^2}\right) + \frac{N+1}{N}\cdot\left(\frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0}\right)\end{aligned} \tag{A.3}$$

Then the first order derivatives of the trip cost ρ_0 w.r.t. C, T, K, x_1 and τ can be expressed as follows:

$$\frac{\partial \rho_0}{\partial C} = \frac{\partial c_t}{\partial C} + \frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0 \partial C},\quad \frac{\partial \rho_0}{\partial T} = \frac{\partial c_t}{\partial T} + \frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0 \partial T},\quad \frac{\partial \rho_0}{\partial K} = \frac{\partial c_r}{\partial K} + \frac{q_0}{N}\cdot\frac{\partial^2 c_r}{\partial q_0 \partial K},\quad \frac{\partial \rho_0}{\partial x_1} = -\frac{q_0}{N}\cdot\frac{\partial^3 u}{\partial x_1 \partial q_0^2},\quad \frac{\partial \rho_0}{\partial \tau} = 1 \tag{A.4}$$

Replacing the results in (A.3) and (A.4) into (A.2) and equating it with (A.1), we have:

$$\begin{aligned}&\left(\frac{q_0}{N}\cdot\left(\frac{\partial^3 u}{\partial q_0^3} - \frac{\partial^2 c_t}{\partial q_0^2} - \frac{\partial^2 c_r}{\partial q_0^2}\right) + \frac{N+1}{N}\cdot\left(\frac{\partial^2 u}{\partial q_0^2} - \frac{\partial c_t}{\partial q_0} - \frac{\partial c_r}{\partial q_0}\right)\right)\cdot dq_0 + \left(\frac{\partial^2 u}{\partial q_0 \partial x_1} + \frac{q_0}{N}\cdot\frac{\partial^3 u}{\partial x_1 \partial q_0^2}\right)\cdot dx_1\\ &= d\tau + \left(\frac{\partial c_t}{\partial C} + \frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0 \partial C}\right)\cdot dC + \left(\frac{\partial c_t}{\partial T} + \frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0 \partial T}\right)\cdot dT + \left(\frac{\partial c_r}{\partial K} + \frac{q_0}{N}\cdot\frac{\partial^2 c_r}{\partial q_0 \partial K}\right)\cdot dK\end{aligned} \tag{A.5}$$

Total differentiating the price of good p_1 as defined in (2.3), we have:

$$dp_1 = \frac{\partial p_1}{\partial q_0}\cdot dq_0 + \frac{\partial p_1}{\partial x_1}\cdot dx_1 = \frac{\partial^2 u}{\partial x_1 \partial q_0}\cdot dq_0 + \frac{\partial^2 u}{\partial x_1^2}\cdot dx_1 \tag{A.6}$$

Rearranging the results in (A.5) and (A.6), we have:

$$A\cdot\begin{pmatrix} dq_0 \\ dx_1 \end{pmatrix} = \begin{pmatrix} d\tau + \left(\frac{\partial c_t}{\partial C} + \frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0 \partial C}\right)dC + \left(\frac{\partial c_t}{\partial T} + \frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0 \partial T}\right)dT + \left(\frac{\partial c_r}{\partial K} + \frac{q_0}{N}\cdot\frac{\partial^2 c_r}{\partial q_0 \partial K}\right)dK \\ dp_1 \end{pmatrix} \tag{A.7}$$

where

$$A \equiv \begin{pmatrix} \frac{q_0}{N}\cdot\left(\frac{\partial^3 u}{\partial q_0^3} - \frac{\partial^2 c_t}{\partial q_0^2} - \frac{\partial^2 c_r}{\partial q_0^2}\right) + \frac{N+1}{N}\cdot\left(\frac{\partial^2 u}{\partial q_0^2} - \frac{\partial c_t}{\partial q_0} - \frac{\partial c_r}{\partial q_0}\right) & \frac{\partial^2 u}{\partial q_0 \partial x_1} + \frac{q_0}{N}\cdot\frac{\partial^3 u}{\partial x_1 \partial q_0^2} \\ \frac{\partial^2 u}{\partial x_1 \partial q_0} & \frac{\partial^2 u}{\partial x_1^2} \end{pmatrix} \tag{A.8}$$

From (A.7) and (A.8), we have:

$$\begin{pmatrix} dq_0 \\ dx_1 \end{pmatrix} = A^{-1} \cdot \begin{pmatrix} d\tau + \left(\frac{\partial c_t}{\partial C} + \frac{q_0}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial C}\right) \cdot dC + \left(\frac{\partial c_t}{\partial T} + \frac{q_0}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial T}\right) \cdot dT + \left(\frac{\partial c_r}{\partial K} + \frac{q_0}{N} \cdot \frac{\partial^2 c_r}{\partial q_0 \partial K}\right) \cdot dK \\ dp_1 \end{pmatrix} \tag{A.9}$$

$$A^{-1} = \begin{pmatrix} h_{00} & h_{01} \\ h_{10} & h_{11} \end{pmatrix}$$

Then the first-order derivative of the trip demand q_0 w.r.t. τ, C, T and K can be expressed as:

$$\begin{aligned} \frac{dq_0}{d\tau} &= h_{00} \\ \frac{dq_0}{dC} &= h_{00} \cdot \left(\frac{\partial c_t}{\partial C} + \frac{q_0}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial C}\right) = \frac{dq_0}{d\tau} \cdot \left(\frac{\partial c_t}{\partial C} + \frac{q_0}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial C}\right) \\ \frac{dq_0}{dT} &= h_{00} \cdot \left(\frac{\partial c_t}{\partial T} + \frac{q_0}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial T}\right) = \frac{dq_0}{d\tau} \cdot \left(\frac{\partial c_t}{\partial T} + \frac{q_0}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial T}\right) \\ \frac{dq_0}{dK} &= h_{00} \cdot \left(\frac{\partial c_r}{\partial K} + \frac{q_0}{N} \cdot \frac{\partial^2 c_r}{\partial q_0 \partial K}\right) = \frac{dq_0}{d\tau} \cdot \left(\frac{\partial c_r}{\partial K} + \frac{q_0}{N} \cdot \frac{\partial^2 c_r}{\partial q_0 \partial K}\right) \end{aligned} \tag{A.10}$$

Appendix B. Optimal charge, capacity, terminal time by welfare- and profit-maximizing airports

Here we derive the optimal charge τ, terminal capacity C, advised dwell time inside terminal T and runway capacity K decided by welfare- and profit-maximizing airports under unregulated situation.

B-1. Optimal airport charge by welfare-maximizing airport (unregulated)

According to (2.14), the first-order derivative of social welfare w.r.t. airport charge τ is:

$$\begin{aligned} \frac{\partial SW}{\partial \tau} &= \left(\frac{\partial u}{\partial q_0} - q_0 \cdot \left(\frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0}\right) - (c_t + c_r) + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0}\right) \cdot \frac{\partial q_0}{\partial \tau} + \left(\frac{\partial u}{\partial x_1} - p_1\right) \cdot \frac{\partial x_1}{\partial \tau} \\ &= \left(p_0 - q_0 \cdot \left(\frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0}\right) + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0}\right) \cdot \frac{\partial q_0}{\partial \tau} \end{aligned} \tag{B.1}$$

Since $\frac{\partial q_0}{\partial \tau} \neq 0$, the first-order condition $\frac{\partial SW}{\partial \tau} = 0$ yields:

$$p_0 = q_0 \cdot \left(\frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0}\right) - \frac{\partial R}{\partial q_0} - \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \tag{B.2}$$

Also, according to (2.10), the optimal ticket fare p_0 that maximizes airline's profit can be expressed as:

$$p_0 = \tau - \frac{q_0}{N} \cdot \frac{\partial p_0}{\partial q_0} = \tau - \frac{q_0}{N} \cdot \left(\frac{\partial \rho_0}{\partial q_0} - \frac{\partial c_t}{\partial q_0} - \frac{\partial c_r}{\partial q_0}\right) \tag{B.3}$$

Equating (B.2) and (B.3), we have:

$$p_0 = \tau - \frac{q_0}{N} \cdot \left(\frac{\partial \rho_0}{\partial q_0} - \frac{\partial c_t}{\partial q_0} - \frac{\partial c_r}{\partial q_0}\right) = q_0 \cdot \left(\frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0}\right) - \frac{\partial R}{\partial q_0} - \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \tag{B.4}$$

Thus, the optimal charge τ_{SW} determined by a welfare-maximizing airport can be expressed as:

$$\begin{aligned} \tau_{SW} &= \frac{q_0}{N} \cdot \frac{\partial \rho_0}{\partial q_0} + q_0 \cdot \frac{N-1}{N} \cdot \left(\frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0}\right) - \frac{\partial R}{\partial q_0} - \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \\ &= q_0 \cdot \frac{\partial \rho_0}{\partial q_0} - q_0 \cdot \frac{N-1}{N} \cdot \frac{\partial p_0}{\partial q_0} - \left(\frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0}\right) \end{aligned} \tag{B.5}$$

B-2. Optimal airport charge by profit-maximizing airport (unregulated)

According to (2.13), the first-order condition of airport profit w.r.t. airport charge can be expressed as:

$$\frac{\partial \pi_o}{\partial \tau} = q_0 + \frac{\partial q_0}{\partial \tau} \cdot \left(\tau + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0}\right) = 0 \tag{B.6}$$

Rearranging (B.6), the optimal charge τ_{π_o} determined by profit-maximizing airport can be expressed as:

$$\tau_{\pi_o} = -\frac{q_0}{\frac{\partial q_0}{\partial \tau}} - \frac{\partial R}{\partial q_0} - \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \tag{B.7}$$

B-3. FOC of terminal capacity by welfare-maximizing airport (unregulated)

The first-order derivative of social welfare w.r.t. terminal capacity can be expressed as:

$$\frac{\partial SW}{\partial C}=\frac{\partial q_0}{\partial C}\cdot\left(\frac{\partial u}{\partial q_0}-q_0\cdot\left(\frac{\partial c_t}{\partial q_0}+\frac{\partial c_r}{\partial q_0}\right)-(c_t+c_r)+\frac{\partial R}{\partial q_0}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial q_0}\right)-q_0\cdot\frac{\partial c_t}{\partial C}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C}+\left(\frac{\partial u}{\partial x_1}-p_1\right)\cdot\frac{\partial x_1}{\partial C}-\frac{\partial c_{KC}}{\partial C} \tag{B.8}$$

Further substitute (B.4) into (B.8), then the first-order condition $\frac{\partial SW}{\partial C}=0$ can be rewritten as:

$$\frac{\partial SW}{\partial C}=-q_0\cdot\frac{\partial c_t}{\partial C}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C}-\frac{\partial c_{KC}}{\partial C}=0 \tag{B.9}$$

Rearranging the terms in (B.9), the first-order condition is equivalent to:

$$\frac{\partial c_{KC}}{\partial C}=-q_0\cdot\frac{\partial c_t}{\partial C}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C} \tag{B.10}$$

B-4. FOC of terminal capacity by profit-maximizing airport (unregulated)

The first-order condition of airport profit w.r.t. terminal capacity can be expressed as:

$$\frac{\partial \pi_o}{\partial C}=\frac{\partial q_0}{\partial C}\cdot\left(\tau+\frac{\partial R}{\partial q_0}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial q_0}\right)+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C}-\frac{\partial c_{KC}}{\partial C}=0 \tag{B.11}$$

Rearranging (B.11), the first-order condition can be rewritten as:

$$\frac{\partial c_{KC}}{\partial C}=\frac{\partial q_0}{\partial C}\cdot\left(\tau+\frac{\partial R}{\partial q_0}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial q_0}\right)+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C} \tag{B.12}$$

Further replacing the optimal airport charge τ_{π_o} as derived in (B.7) into (B.12), we have:

$$\frac{\partial c_{KC}}{\partial C}=-\frac{q_0}{\frac{\partial q_0}{\partial \tau}}\cdot\frac{\partial q_0}{\partial C}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C} \tag{B.13}$$

Recall (A.10) that $\frac{dq_0}{dC}=\frac{dq_0}{d\tau}\cdot\left(\frac{\partial c_t}{\partial C}+\frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial C}\right)$, then (B.13) can be simplified as follows:

$$\frac{\partial c_{KC}}{\partial C}=-\frac{q_0}{\frac{\partial q_0}{\partial \tau}}\cdot\frac{dq_0}{d\tau}\cdot\left(\frac{\partial c_t}{\partial C}+\frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial C}\right)+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C}=-q_0\cdot\frac{\partial c_t}{\partial C}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C}-\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial C} \tag{B.14}$$

B-5. FOC of dwell time at airport terminal by welfare-maximizing airport (unregulated)

The first-order derivative of social welfare w.r.t. terminal time can be expressed as:

$$\frac{\partial SW}{\partial T}=\left(\frac{\partial u}{\partial q_0}-q_0\cdot\left(\frac{\partial c_t}{\partial q_0}+\frac{\partial c_r}{\partial q_0}\right)-(c_t+c_r)+\frac{\partial R}{\partial q_0}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial q_0}\right)\cdot\frac{\partial q_0}{\partial T}-q_0\cdot\frac{\partial c_t}{\partial T}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial T}+\left(\frac{\partial u}{\partial x_1}-p_1\right)\cdot\frac{\partial x_1}{\partial T} \tag{B.15}$$

Further replace (B.4) into (B.15), the first-order condition $\frac{\partial SW}{\partial T}=0$ yields:

$$\frac{\partial SW}{\partial T}=-q_0\cdot\frac{\partial c_t}{\partial T}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial T}=0 \tag{B.16}$$

Rearranging (B.17), the first-order condition can be expressed as:

$$q_0\cdot\frac{\partial c_t}{\partial T}=\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial T} \tag{B.17}$$

B-6. FOC of dwell time at airport terminal by profit-maximizing airport (unregulated)

The first-order condition of airport profit w.r.t. terminal time can be expressed as:

$$\frac{\partial \pi_o}{\partial T}=\frac{\partial q_0}{\partial T}\cdot\left(\tau+\frac{\partial R}{\partial q_0}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial q_0}\right)+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial T}=0 \tag{B.18}$$

Rearranging (B.18), the FOC can be equivalently expressed as:

$$\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial T}=-\frac{\partial q_0}{\partial T}\cdot\left(\tau+\frac{\partial R}{\partial q_0}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial q_0}\right) \tag{B.19}$$

Further replacing the optimal airport charge τ_{π_o} as derived in (B.7) into (B.19), we have:

$$\frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial T} = \frac{\partial q_0}{\partial T} \cdot \frac{q_0}{\frac{\partial q_0}{\partial \tau}} \tag{B.20}$$

Recall (A.10) that $\frac{dq_0}{dT} = \frac{dq_0}{d\tau} \cdot \left(\frac{\partial c_t}{\partial T} + \frac{q_0}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial T} \right)$, then (B.20) can be simplified to:

$$q_0 \cdot \frac{\partial c_t}{\partial T} = \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial T} - \frac{q_0^2}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial T} \tag{B.21}$$

B-7. FOC of runway capacity at airport terminal by profit-maximizing airport (unregulated)

The first-order derivative of social welfare w.r.t. runway capacity can be expressed as:

$$\frac{\partial SW}{\partial K} = \left(\frac{\partial u}{\partial q_0} - q_0 \cdot \left(\frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0} \right) - (c_t + c_r) + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \right) \cdot \frac{\partial q_0}{\partial K} - q_0 \cdot \frac{\partial c_r}{\partial K} + \left(\frac{\partial u}{\partial x_1} - p_1 \right) \cdot \frac{\partial x_1}{\partial K} - \frac{\partial c_{KC}}{\partial K} \tag{B.22}$$

Further replace (2.10) into (B.22), the first-order condition $\frac{\partial SW}{\partial K} = 0$ yields:

$$\frac{\partial SW}{\partial K} = -q_0 \cdot \frac{\partial c_r}{\partial K} - \frac{\partial c_{KC}}{\partial K} = 0 \tag{B.23}$$

Rearranging (B.23), the first-order condition can be expressed as:

$$\frac{\partial c_{KC}}{\partial K} = -q_0 \cdot \frac{\partial c_r}{\partial K} \tag{B.24}$$

B-8. FOC of runway capacity at airport terminal by profit-maximizing airport (unregulated)

The first-order condition of airport profit w.r.t. runway capacity can be expressed as:

$$\frac{\partial \pi_o}{\partial K} = \frac{\partial q_0}{\partial K} \cdot \left(\tau + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \right) - \frac{\partial c_{KC}}{\partial K} = 0 \tag{B.25}$$

Rearranging (B.25), the FOC can be equivalently expressed as:

$$\frac{\partial c_{KC}}{\partial K} = \frac{\partial q_0}{\partial K} \cdot \left(\tau + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \right) \tag{B.26}$$

Further replacing the optimal airport charge τ_{π_o} as derived in (B.7) into (B.26), we have:

$$\frac{\partial c_{KC}}{\partial K} = -\frac{\partial q_0}{\partial K} \cdot \frac{q_0}{\frac{\partial q_0}{\partial \tau}} \tag{B.27}$$

Recall (A.10) that $\frac{dq_0}{dK} = \frac{dq_0}{d\tau} \cdot \left(\frac{\partial c_r}{\partial K} + \frac{q_0}{N} \cdot \frac{\partial^2 c_r}{\partial q_0 \partial K} \right)$, then (B.27) can be simplified to:

$$\frac{\partial c_{KC}}{\partial K} = -q_0 \cdot \frac{\partial c_r}{\partial K} - \frac{q_0^2}{N} \cdot \frac{\partial^2 c_r}{\partial q_0 \partial K} \tag{B.28}$$

Appendix C. Proof of Proposition 1

C-1. Optimal airport charge by welfare-maximizing airport under single-till regulation

According to (3.3), the first-order condition w.r.t. airport charge τ can be expressed as:

$$\frac{\partial \Lambda}{\partial \tau} = \frac{\partial SW}{\partial \tau} - \lambda \cdot \frac{\partial \pi_o}{\partial \tau} = 0 \tag{C.1}$$

According to (B.1) and (B.6), the FOC in (C.1) can be rewritten as:

$$\lambda \cdot q_0 = \frac{\partial q_0}{\partial \tau} \cdot \left((1-\lambda) \left(\tau + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \right) - \left(\frac{q_0}{N} \cdot \frac{\partial p_0}{\partial q_0} + q_0 \left(\frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0} \right) \right) \right) \tag{C.2}$$

Rearranging the FOC in (C.2), the optimal airport charge under single-till regulation is:

$$\begin{aligned}\tau_{SW}^{\sin} &= \frac{\lambda}{1-\lambda}\cdot\frac{q_0}{\frac{\partial q_0}{\partial \tau}}+\frac{1}{1-\lambda}\left(\frac{q_0}{N}\cdot\frac{\partial \rho_0}{\partial q_0}+q_0\cdot\frac{N-1}{N}\left(\frac{\partial c_t}{\partial q_0}+\frac{\partial c_r}{\partial q_0}\right)\right)-\left(\frac{\partial R}{\partial q_0}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial q_0}\right)\\ &= \frac{\lambda}{1-\lambda}\cdot\frac{q_0}{\frac{\partial q_0}{\partial \tau}}+\frac{1}{1-\lambda}\cdot\left(q_0\cdot\frac{\partial \rho_0}{\partial q_0}+q_0\cdot\left(\frac{1}{N}-1\right)\cdot\frac{\partial p_0}{\partial q_0}\right)-\left(\frac{\partial R}{\partial q_0}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial q_0}\right)\end{aligned}\tag{C.3}$$

C-2. FOC of terminal capacity by welfare-maximizing airport under single-till regulation

The first-order condition w.r.t. terminal capacity C can be expressed as:

$$\frac{\partial \Lambda}{\partial C}=\frac{\partial SW}{\partial C}-\lambda\cdot\frac{\partial \pi_o}{\partial C}=0\tag{C.4}$$

According to (B.15) and (B.11), above FOC can be equivalently expressed as:

$$\frac{\partial \Lambda}{\partial C}=\left((1-\lambda)\left(\tau+\frac{\partial R}{\partial q_0}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial q_0}\right)-\left(\frac{q_0}{N}\cdot\frac{\partial p_0}{\partial q_0}+q_0\left(\frac{\partial c_t}{\partial q_0}+\frac{\partial c_r}{\partial q_0}\right)\right)\right)\frac{\partial q_0}{\partial C}+(1-\lambda)\left(\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C}-\frac{\partial c_{KC}}{\partial C}\right)-q_0\frac{\partial c_t}{\partial C}=0\tag{C.5}$$

Recall (A.10) that $\frac{dq_0}{dC}=\frac{dq_0}{d\tau}\cdot\left(\frac{\partial c_t}{\partial C}+\frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial C}\right)$, also the FOC in (C.2), then (C.5) can be simplified to:

$$\begin{aligned}\frac{\partial \Lambda}{\partial C}&=\lambda\cdot\frac{q_0}{\frac{\partial q_0}{\partial \tau}}\cdot\frac{dq_0}{d\tau}\cdot\left(\frac{\partial c_t}{\partial C}+\frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial C}\right)+(1-\lambda)\cdot\left(\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C}-\frac{\partial c_{KC}}{\partial C}\right)-q_0\cdot\frac{\partial c_t}{\partial C}\\ &=\lambda\cdot\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial C}+(1-\lambda)\cdot\left(\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C}-\frac{\partial c_{KC}}{\partial C}-q_0\cdot\frac{\partial c_t}{\partial C}\right)=0\end{aligned}\tag{C.6}$$

Further derive the FOC w.r.t. regulatory waste and Lagrangian multiplier, we have:

$$\begin{aligned}&\mu\cdot\frac{\partial \Lambda}{\partial \mu}=0,\qquad \frac{\partial \Lambda}{\partial \mu}\le 0,\qquad \lambda\cdot\frac{\partial \Lambda}{\partial \lambda}=0,\qquad \frac{\partial \Lambda}{\partial \lambda}\ge 0\\ &\mu\cdot(-1+\lambda)=0,\qquad -1+\lambda\le 0,\qquad \lambda\cdot(\mu-\pi_o)=0,\qquad \mu-\pi_o\ge 0\end{aligned}\tag{C.7}$$

Therefore, we either have:

$$\begin{aligned}&\text{(i)}\ \ \lambda=1,\\ &\text{(ii)}\ \mu=0,\quad 0\le\lambda\le 1\end{aligned}\tag{C.8}$$

For case (i), when $\lambda = 1$, we have $\frac{\partial \Lambda}{\partial C}=\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial C}$. According to the analysis in (2.8), only when $q_0=\bar{q}_0$, we have $\frac{\partial \Lambda}{\partial C}=0$. Hence under most of the situations, $\frac{\partial \Lambda}{\partial C}\ne 0$, which violates the FOC in (C.4). For case (ii), when $\mu = 0$, $0 \le \lambda \le 1$, from (C.6), we have:

$$\lambda\cdot\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial C}+(1-\lambda)\cdot\left(\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C}-\frac{\partial c_{KC}}{\partial C}-q_0\cdot\frac{\partial c_t}{\partial C}\right)=0\tag{C.9}$$

Rearranging the terms in (C.9), the FOC can be simplified to:

$$-q_0\cdot\frac{\partial c_t}{\partial C}=-\frac{\lambda}{1-\lambda}\cdot\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial C}+\frac{\partial c_{KC}}{\partial C}-\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C}\tag{C.10}$$

C-3. FOC of dwell time at terminal by welfare-maximizing airport under single-till regulation

The first-order condition w.r.t. terminal time T can be expressed as:

$$\frac{\partial \Lambda}{\partial T}=\frac{\partial SW}{\partial T}-\lambda\cdot\frac{\partial \pi_o}{\partial T}=0\tag{C.11}$$

According to (B.16) and (B.18), the FOC can be rewritten as:

$$\frac{\partial \Lambda}{\partial T}=\frac{\partial q_0}{\partial T}\cdot\left((1-\lambda)\left(\tau+\frac{\partial R}{\partial q_0}+\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial q_0}\right)-\left(\frac{q_0}{N}\left(\frac{\partial p_0}{\partial q_0}\right)+q_0\left(\frac{\partial c_t}{\partial q_0}+\frac{\partial c_r}{\partial q_0}\right)\right)\right)+(1-\lambda)\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial T}-q_0\frac{\partial c_t}{\partial T}=0\tag{C.12}$$

Recall (A.10) that $\frac{dq_0}{dT}=\frac{dq_0}{d\tau}\cdot\left(\frac{\partial c_t}{\partial T}+\frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial T}\right)$, also the FOC in (C.2), then (C.12) can be simplified to:

$$\frac{\partial \Lambda}{\partial T}=\lambda\cdot\frac{q_0}{\frac{\partial q_0}{\partial \tau}}\cdot\frac{\partial q_0}{\partial T}+(1-\lambda)\cdot\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial T}-q_0\cdot\frac{\partial c_t}{\partial T}=\lambda\cdot\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial T}+(1-\lambda)\left(\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial T}-q_0\frac{\partial c_t}{\partial T}\right)\tag{C.13}$$

Similar to (C.7)-(C.8), when $\lambda = 1$, we have $\frac{\partial \Lambda}{\partial T}=\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial T}$. Since $\frac{\partial^2 c_t}{\partial q_0\partial T}=\frac{\beta_2^2\beta_3(v_w-v_s)t_s}{(K-q_0)^2}$, we have $\frac{\partial \Lambda}{\partial T}=\frac{\beta_2^2\beta_3 q_0^2(v_w-v_s)t_s}{N\cdot(K-q_0)^2}$. Unless $v_w-v_s=0$, i.e., v_w

$= v_s$, we have $\frac{\partial \Lambda}{\partial T} = 0$, otherwise, it violates the FOC in (C.11), thus $\lambda \neq 1$. Then we derive the case when $\mu = 0$, $0 \leq \lambda \leq 1$. The FOC in (C.13) is equivalent to:

$$\frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial T} = q_0 \cdot \frac{\partial c_t}{\partial T} - \frac{\lambda}{1-\lambda} \cdot \frac{q_0^2}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial T} \tag{C.14}$$

C-4. FOC of runway capacity by welfare-maximizing airport under single-till regulation

The first-order condition w.r.t. runway capacity K can be expressed as:

$$\frac{\partial \Lambda}{\partial K} = \frac{\partial SW}{\partial K} - \lambda \cdot \frac{\partial \pi_o}{\partial K} = 0 \tag{C.15}$$

According to (B.22) and (B.25), the FOC can be rewritten as:

$$\frac{\partial \Lambda}{\partial K} = \frac{\partial q_0}{\partial K}\left((1-\lambda)\left(\tau + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0}\right) - \left(\frac{q_0}{N} \cdot \frac{\partial p_0}{\partial q_0} + q_0\left(\frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0}\right)\right)\right) - (1-\lambda)\frac{\partial c_{KC}}{\partial K} - q_0\frac{\partial c_r}{\partial K} = 0 \tag{C.16}$$

Recall (A.10) that $\frac{dq_0}{dK} = \frac{dq_0}{d\tau} \cdot \left(\frac{\partial c_r}{\partial K} + \frac{q_0}{N} \cdot \frac{\partial^2 c_r}{\partial q_0 \partial K}\right)$, also the FOC in (C.2), then (C.16) can be simplified to:

$$\frac{\partial \Lambda}{\partial K} = \lambda q_0\left(\frac{\partial c_r}{\partial K} + \frac{q_0}{N} \cdot \frac{\partial^2 c_r}{\partial q_0 \partial K}\right) - (1-\lambda)\frac{\partial c_{KC}}{\partial K} - q_0\frac{\partial c_r}{\partial K} = \lambda\frac{q_0^2}{N} \cdot \frac{\partial^2 c_r}{\partial q_0 \partial K} + (\lambda - 1)\left(\frac{\partial c_{KC}}{\partial K} + q_0\frac{\partial c_r}{\partial K}\right) = 0 \tag{C.17}$$

Similar to (C.7)-(C.8), when $\lambda = 1$, we have $\frac{\partial \Lambda}{\partial K} = \frac{q_0^2}{N} \cdot \frac{\partial^2 c_r}{\partial q_0 \partial K} = 0$ which violates $\frac{\partial^2 c_r}{\partial q_0 \partial K} = -\frac{v_r}{w^2(wK-q_0)^4} < 0$, thus $\lambda \neq 1$. Further rearranging the FOC in (C.17), we have:

$$\frac{\partial c_{KC}}{\partial K} = \frac{\lambda}{1-\lambda} \cdot \frac{q_0^2}{N} \cdot \frac{\partial^2 c_r}{\partial q_0 \partial K} - q_0 \cdot \frac{\partial c_r}{\partial K} \tag{C.18}$$

This completes the proof of **Proposition 1**. ∎

Appendix D. Proof of Proposition 2

D-1. Optimal airport charge by welfare-maximizing airport under dual-till regulation

According to (3.15), the first-order condition w.r.t. airport charge τ can be expressed as:

$$\frac{\partial \Lambda}{\partial \tau} = \frac{\partial SW}{\partial \tau} - \lambda \cdot \frac{\partial(q_0 \cdot \tau - c_{KC} - F \cdot \alpha_{KC} - \mu)}{\partial \tau} = \frac{\partial SW}{\partial \tau} - \lambda \cdot \left(q_0 + \tau \cdot \frac{\partial q_0}{\partial \tau}\right) = 0 \tag{D.1}$$

According to (B.1), the FOC in (D.1) can be rewritten as:

$$\lambda \cdot q_0 = \frac{\partial q_0}{\partial \tau} \cdot \left(\tau(1-\lambda) + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} - \frac{q_0}{N} \cdot \frac{\partial p_0}{\partial q_0} - q_0\left(\frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0}\right)\right) \tag{D.2}$$

Rearranging the FOC in (D.2), the optimal airport charge can be expressed as:

$$\begin{aligned}\tau_{SW}^{dual} &= \frac{\lambda}{1-\lambda} \cdot \frac{q_0}{\frac{\partial q_0}{\partial \tau}} - \frac{1}{1-\lambda} \cdot \left(\frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} - \frac{q_0}{N} \cdot \frac{\partial p_0}{\partial q_0} - q_0 \cdot \left(\frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0}\right)\right) \\ &= \frac{\lambda}{1-\lambda} \cdot \frac{q_0}{\frac{\partial q_0}{\partial \tau}} + \frac{1}{1-\lambda} \cdot \left(-\frac{\partial R}{\partial q_0} - \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} + q_0 \cdot \frac{\partial \rho_0}{\partial q_0} + q_0 \cdot \left(\frac{1}{N} - 1\right) \cdot \frac{\partial p_0}{\partial q_0}\right)\end{aligned} \tag{D.3}$$

D-2. FOC of terminal capacity by welfare-maximizing airport under dual-till regulation

The first-order condition w.r.t. terminal capacity C can be expressed as:

$$\frac{\partial \Lambda}{\partial C} = \frac{\partial SW}{\partial C} - \lambda \cdot \frac{\partial(q_0 \cdot \tau - c_{KC} - F \cdot \alpha_{KC} - \mu)}{\partial C} = \frac{\partial SW}{\partial C} - \lambda \cdot \left(\tau \cdot \frac{\partial q_0}{\partial C} - \frac{\partial c_{KC}}{\partial C} - F \cdot \frac{\partial \alpha_{KC}}{\partial C}\right) = 0 \tag{D.4}$$

According to (B.8), the FOC can be expressed as:

$$\begin{aligned}\frac{\partial \Lambda}{\partial C} &= -(1-\lambda) \cdot \frac{\partial c_{KC}}{\partial C} - q_0 \cdot \frac{\partial c_t}{\partial C} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial C} + \lambda F \cdot \frac{\partial \alpha_{KC}}{\partial C} \\ &+ \left(\tau \cdot (1-\lambda) + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} - \frac{q_0}{N} \cdot \frac{\partial p_0}{\partial q_0} - q_0 \cdot \left(\frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0}\right)\right) \cdot \frac{\partial q_0}{\partial C} = 0\end{aligned} \tag{D.5}$$

From the FOC in (D.2), the FOC in (D.5) can be simplified to:

$$\frac{\partial\Lambda}{\partial C} = -(1-\lambda)\cdot\frac{\partial c_{KC}}{\partial C} - q_0\cdot\frac{\partial c_t}{\partial C} + \frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C} + \lambda F\cdot\frac{\partial\alpha_{KC}}{\partial C} + \lambda\cdot\frac{q_0}{\frac{\partial q_0}{\partial\tau}}\cdot\frac{\partial q_0}{\partial C} = 0 \tag{D.6}$$

Recall (A.10) that $\frac{dq_0}{dC} = \frac{dq_0}{d\tau}\cdot\left(\frac{\partial c_t}{\partial C} + \frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial C}\right)$, above FOC can be simplified to:

$$-q_0\cdot\frac{\partial c_t}{\partial C} = -\frac{1}{1-\lambda}\cdot\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial C} - \frac{\lambda}{1-\lambda}\cdot\left(\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial C} + F\cdot\frac{\partial\alpha_{KC}}{\partial C}\right) + \frac{\partial c_{KC}}{\partial C} \tag{D.7}$$

D-3. FOC of terminal time by welfare-maximizing airport under dual-till regulation

The first-order condition w.r.t. terminal time T can be expressed as:

$$\frac{\partial\Lambda}{\partial T} = \frac{\partial SW}{\partial T} - \lambda\cdot\frac{\partial(q_0\cdot\tau - c_{KC} - F\cdot\alpha_{KC} - \mu)}{\partial T} = \frac{\partial SW}{\partial T} - \lambda\tau\cdot\frac{\partial q_0}{\partial T} = 0 \tag{D.8}$$

According to (B.16), the FOC can be rewritten as:

$$\frac{\partial\Lambda}{\partial T} = \left(\tau\cdot(1-\lambda) - \frac{q_0}{N}\cdot\frac{\partial p_0}{\partial q_0} - q_0\left(\frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0}\right) + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial q_0}\right)\cdot\frac{\partial q_0}{\partial T} - q_0\cdot\frac{\partial c_t}{\partial T} + \frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial T} = 0 \tag{D.9}$$

From the FOC in (D.2), the FOC in (D.9) can be simplified to:

$$\frac{\partial\Lambda}{\partial T} = \lambda\cdot\frac{q_0}{\frac{\partial q_0}{\partial\tau}}\cdot\frac{\partial q_0}{\partial T} - q_0\cdot\frac{\partial c_t}{\partial T} + \frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial T} \tag{D.10}$$

Recall (A.10) that $\frac{dq_0}{dT} = \frac{dq_0}{d\tau}\cdot\left(\frac{\partial c_t}{\partial T} + \frac{q_0}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial T}\right)$, then (D.10) can be simplified to:

$$\frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial T} = (1-\lambda)\cdot q_0\cdot\frac{\partial c_t}{\partial T} - \lambda\cdot\frac{q_0^2}{N}\cdot\frac{\partial^2 c_t}{\partial q_0\partial T} \tag{D.11}$$

D-4. FOC of runway capacity by welfare-maximizing airport under dual-till regulation

The first-order condition w.r.t. runway capacity K can be expressed as:

$$\frac{\partial\Lambda}{\partial K} = \frac{\partial SW}{\partial K} - \lambda\cdot\frac{\partial(q_0\cdot\tau - c_{KC} - F\cdot\alpha_{KC} - \mu)}{\partial K} = \frac{\partial SW}{\partial K} - \lambda\left(\tau\cdot\frac{\partial q_0}{\partial K} - \frac{\partial c_{KC}}{\partial K} - F\cdot\frac{\partial\alpha_{KC}}{\partial K}\right) = 0 \tag{D.12}$$

According to (B.22), the FOC can be rewritten as:

$$\frac{\partial\Lambda}{\partial K} = \left(\tau\cdot(1-\lambda) + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s}\cdot\frac{\partial t_s}{\partial q_0} - \frac{q_0}{N}\cdot\frac{\partial p_0}{\partial q_0} - q_0\left(\frac{\partial c_t}{\partial q_0} + \frac{\partial c_r}{\partial q_0}\right)\right)\cdot\frac{\partial q_0}{\partial K} - q_0\frac{\partial c_r}{\partial K} - (1-\lambda)\frac{\partial c_{KC}}{\partial K} + \lambda F\cdot\frac{\partial\alpha_{KC}}{\partial K} = 0 \tag{D.13}$$

From the FOC in (D.2), the FOC in (D.13) can be simplified to:

$$\frac{\partial\Lambda}{\partial K} = \lambda\cdot\frac{q_0}{\frac{\partial q_0}{\partial\tau}}\cdot\frac{\partial q_0}{\partial K} - q_0\cdot\frac{\partial c_r}{\partial K} - (1-\lambda)\frac{\partial c_{KC}}{\partial K} + \lambda F\cdot\frac{\partial\alpha_{KC}}{\partial K} \tag{D.14}$$

Recall (A.10) that $\frac{dq_0}{dK} = \frac{dq_0}{d\tau}\cdot\left(\frac{\partial c_r}{\partial K} + \frac{q_0}{N}\cdot\frac{\partial^2 c_r}{\partial q_0\partial K}\right)$, the FOC in (D.14) can be rewritten as:

$$\frac{\partial c_{KC}}{\partial K} = -q_0\cdot\frac{\partial c_r}{\partial K} + \frac{\lambda}{1-\lambda}\cdot\left(\frac{q_0^2}{N}\cdot\frac{\partial^2 c_r}{\partial q_0\partial K} + F\cdot\frac{\partial\alpha_{KC}}{\partial K}\right) \tag{D.15}$$

This completes the proof of **Proposition 2.** ∎

Appendix E. Proof of Proposition 3

E-1. Optimal airport charge by profit-maximizing airport under dual-till regulation

According to (3.27), the first-order condition w.r.t. airport charge τ can be expressed as:

$$\frac{\partial\Lambda}{\partial\tau} = \frac{\partial\pi_o}{\partial\tau} - \lambda\cdot\frac{\partial(q_0\cdot\tau - c_{KC} - F\cdot\alpha_{KC} - \mu)}{\partial\tau} = \frac{\partial\pi_o}{\partial\tau} - \lambda\cdot\left(q_0 + \tau\cdot\frac{\partial q_0}{\partial\tau}\right) = 0 \tag{E.1}$$

According to (B.6), the FOC in (E.1) can be rewritten as:

$$\frac{\partial \Lambda}{\partial \tau} = q_0 + \frac{\partial q_0}{\partial \tau} \cdot \left(\tau + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \right) - \lambda \cdot \left(q_0 + \tau \cdot \frac{\partial q_0}{\partial \tau} \right) = 0 \tag{E.2}$$

Rearranging (E.2), we have:

$$(1 - \lambda) \cdot q_0 = -\frac{\partial q_0}{\partial \tau} \left((1 - \lambda) \cdot \tau + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \right) \tag{E.3}$$

Then the optimal airport charge that maximizes the airport profit under dual-till regulation is:

$$\tau_{\pi_o}^{dual} = -\frac{q_0}{\frac{\partial q_0}{\partial \tau}} - \frac{1}{1 - \lambda} \cdot \left(\frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \right) \tag{E.4}$$

E-2. FOC of terminal capacity by profit-maximizing airport under dual-till regulation

The first-order condition w.r.t. terminal capacity C can be expressed as:

$$\frac{\partial \Lambda}{\partial C} = \frac{\partial \pi_o}{\partial C} - \lambda \cdot \frac{\partial (q_0 \cdot \tau - c_{KC} - F \cdot \alpha_{KC} - \mu)}{\partial C} = \frac{\partial \pi_o}{\partial C} - \lambda \cdot \left(\tau \cdot \frac{\partial q_0}{\partial C} - \frac{\partial c_{KC}}{\partial C} - F \cdot \frac{\partial \alpha_{KC}}{\partial C} \right) = 0 \tag{E.5}$$

According to (B.11), the FOC can be expressed as:

$$\frac{\partial \Lambda}{\partial C} = \left((1 - \lambda) \cdot \tau + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} + \frac{\partial R}{\partial q_0} \right) \cdot \frac{\partial q_0}{\partial C} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial C} + \lambda F \cdot \frac{\partial \alpha_{KC}}{\partial C} - (1 - \lambda) \cdot \frac{\partial c_{KC}}{\partial C} = 0 \tag{E.6}$$

From the FOC in (E.3), the FOC in (E.6) can be simplified to:

$$\frac{\partial \Lambda}{\partial C} = (1 - \lambda) \cdot \frac{q_0}{-\frac{\partial q_0}{\partial \tau}} \cdot \frac{\partial q_0}{\partial C} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial C} + \lambda F \cdot \frac{\partial \alpha_{KC}}{\partial C} - (1 - \lambda) \cdot \frac{\partial c_{KC}}{\partial C} = 0 \tag{E.7}$$

Recall (A.10) that $\frac{dq_0}{dC} = \frac{dq_0}{d\tau} \cdot \left(\frac{\partial c_t}{\partial C} + \frac{q_0}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial C} \right)$, above FOC can be simplified to:

$$-q_0 \cdot \frac{\partial c_t}{\partial C} = \frac{\partial c_{KC}}{\partial C} + \frac{q_0^2}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial C} - \frac{1}{1 - \lambda} \cdot \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial C} - \frac{\lambda}{1 - \lambda} \cdot F \cdot \frac{\partial \alpha_{KC}}{\partial C} \tag{E.8}$$

E-3. FOC of terminal time by profit-maximizing airport under dual-till regulation

The first-order condition w.r.t. terminal time T can be expressed as:

$$\frac{\partial \Lambda}{\partial T} = \frac{\partial \pi_o}{\partial T} - \lambda \cdot \frac{\partial (q_0 \cdot \tau - c_{KC} - F \cdot \alpha_{KC} - \mu)}{\partial T} = \frac{\partial \pi_o}{\partial T} - \lambda \tau \cdot \frac{\partial q_0}{\partial T} = 0 \tag{E.9}$$

According to (B.18), the FOC can be rewritten as:

$$\frac{\partial \Lambda}{\partial T} = \left((1 - \lambda) \cdot \tau + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \right) \cdot \frac{\partial q_0}{\partial T} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial T} = 0 \tag{E.10}$$

From the FOC in (E.3), the FOC in (E.10) can be simplified to:

$$\frac{\partial \Lambda}{\partial T} = (1 - \lambda) \cdot \frac{q_0}{-\frac{\partial q_0}{\partial \tau}} \cdot \frac{\partial q_0}{\partial T} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial T} = 0 \tag{E.11}$$

Recall (A.10) that $\frac{dq_0}{dT} = \frac{dq_0}{d\tau} \cdot \left(\frac{\partial c_t}{\partial T} + \frac{q_0}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial T} \right)$, then (E.11) can be simplified to:

$$\frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial T} = (1 - \lambda) \cdot q_0 \cdot \left(\frac{\partial c_t}{\partial T} + \frac{q_0}{N} \cdot \frac{\partial^2 c_t}{\partial q_0 \partial T} \right) \tag{E.12}$$

E-4. FOC of runway capacity by profit-maximizing airport under dual-till regulation

The first-order condition w.r.t. runway capacity K can be expressed as:

$$\frac{\partial \Lambda}{\partial K} = \frac{\partial \pi_o}{\partial K} - \lambda \cdot \frac{\partial (q_0 \cdot \tau - c_{KC} - F \cdot \alpha_{KC} - \mu)}{\partial K} = \frac{\partial \pi_o}{\partial K} - \lambda \cdot \left(\tau \cdot \frac{\partial q_0}{\partial K} - \frac{\partial c_{KC}}{\partial K} - F \cdot \frac{\partial \alpha_{KC}}{\partial K} \right) = 0 \tag{E.13}$$

According to (B.25), the FOC can be rewritten as:

$$\frac{\partial \Lambda}{\partial K} = \left((1 - \lambda) \cdot \tau + \frac{\partial R}{\partial q_0} + \frac{\partial R}{\partial t_s} \cdot \frac{\partial t_s}{\partial q_0} \right) \cdot \frac{\partial q_0}{\partial K} - (1 - \lambda) \cdot \frac{\partial c_{KC}}{\partial K} + \lambda F \cdot \frac{\partial \alpha_{KC}}{\partial K} = 0 \tag{E.14}$$

From the FOC in (E.3), the FOC in (E.14) can be simplified to:

$$\frac{\partial\Lambda}{\partial K} = (1-\lambda)\cdot\frac{q_0}{-\frac{\partial q_0}{\partial\tau}}\cdot\frac{\partial q_0}{\partial K} - (1-\lambda)\cdot\frac{\partial c_{KC}}{\partial K} + \lambda F\cdot\frac{\partial\alpha_{KC}}{\partial K} = 0 \tag{E.15}$$

Recall (A.10) that $\frac{dq_0}{dK} = \frac{dq_0}{d\tau}\cdot\left(\frac{\partial c_r}{\partial K} + \frac{q_0}{N}\cdot\frac{\partial^2 c_r}{\partial q_0\partial K}\right)$, the FOC in (E.15) can be rewritten as:

$$\frac{\partial c_{KC}}{\partial K} = -q_0\left(\frac{\partial c_r}{\partial K} + \frac{q_0}{N}\cdot\frac{\partial^2 c_r}{\partial q_0\partial K}\right) + \frac{\lambda}{1-\lambda}\cdot F\cdot\frac{\partial\alpha_{KC}}{\partial K} \tag{E.16}$$

This completes the proof of **Proposition 3**. ∎

Data availability

No data was used for the research described in the article.

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