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# Single-till regulation, dual-till regulation, and regulatory capture: When does a regulatory authority favor single-till regulation over dual-till regulation?

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ABSTRACT

This paper analyzes single-till regulation and dual-till regulation of a monopoly infrastructure, and clarifies conditions under which different stakeholders prefer one regulation type to the other. When a regulator maximizes the utility of consumers, the profit of service providers, or the weighted sum of both, it prefers single-till regulation when there is a positive profit from the non-core good. On the contrary, when the regulator maximizes the profit of the (infrastructure) monopoly, dual-till regulation is preferred if the profit from the non-core good is positive. Under a positive profit from the non-core good, consumers and service providers prefer single-till regulation, while the monopoly prefers dual-till regulation. Consumers and service providers thus have an opposite preference to the monopoly. If a regulator implements dual-till regulation under a positive profit from the non-core good, it reveals its preference for the monopoly's profit, suggesting that the regulator may be captured by the monopoly.

## 1. Introduction

Which type of regulation, single-till or dual-till regulation, is more socially desirable is crucial in regulatory policy when a regulated monopoly (e.g., airport) produces its core good (e.g., aeronautical service) and non-core good (e.g., non-aeronautical service). Kidokoro and Zhang (2022) examine this question theoretically, and demonstrate that the answer depends largely on the following two conditions. The first condition is whether the solutions under social welfare maximization yield a positive or negative regulatory profit; and second, whether the profit of non-core business is positive or negative. For example, if the solution under unconstrained welfare maximization yields a negative regulatory profit and the profit from non-core business is positive, then single-till regulation yields higher welfare.

When implementing regulations in practice, the second condition is clear and relatively easy to verify. For instance, large airports often earn large profits from non-aeronautical service (i.e. non-core businesses in the context of an airport).[1] In contrast, the first condition is more difficult to apply in practice, because the regulator needs to know a hypothetical regulatory profit under unconstrained welfare maximization, which is not directly observable.

In this paper, we show that the first condition is not needed in certain specific cases. If the first condition is unnecessary, given that the second condition is directly observable, a regulator can arrive at which regulation, single-till or dual-till, is preferable much more easily. Our result is therefore effective in helping design regulatory policies in practice. Moreover, our method can, as explained below, be used to unveil the regulator's preference for the benefit of users (i.e., consumers and service providers) or for the profit of a regulated monopoly.

Our main results are as follows: First, when a regulator maximizes the utility of consumers (e.g., air passengers), single-till regulation is desirable when the non-core good yields a positive profit. In this case, under unconstrained social welfare maximization (maximization of consumers' utility), the optimal prices of the core and non-core goods are zero, because lowering prices makes consumers' utility higher. Zero prices make the regulatory profit negative. Thus, the first condition is automatically determined by the assumption that the regulator maximizes consumers' utility, and only the second condition of a positive

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[1] For instance, according to Heathrow (2020), non-aeronautical income of Heathrow airport in London is 1239 million pound in 2019. This is smaller than aeronautical income of 1831 million pound, but still larger than the total operating cost of 1149 million pound.

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profit from the non-core good matters.

Second, when the regulator maximizes the profit of service providers (e.g., airlines who use the airport as an input), single-till regulation is also desirable under a positive profit from the non-core good. In this case, under unconstrained social welfare maximization (maximization of the profits of service providers), the optimal prices of the core and non-core goods are zero. This is because: i) lowering price of the core good makes the profit of service providers higher; and ii) lowering price of the non-core good makes the demand for the core good higher, which in turn increases the profit of service providers, under the assumption that the core and non-core goods are complementary. Zero prices make the regulatory profit negative. Thus, again, the first condition is automatically determined by the assumption that the regulator maximizes the profit of service providers, and only the second condition of a positive profit from the non-core good matters. Third, as a natural consequence of the above two results, single-till regulation is preferred under a positive profit from the non-core good, when the regulator maximizes the weighted sum of consumers' utility and the profits of service providers.

Fourth, when the regulator maximizes the profit of the (infrastructure) monopoly, dual-till regulation is preferred if the profit from the non-core good is positive. This is because the monopoly's profit is larger when the positive profit from the non-core good is unregulated. Consequently, if the profit from the non-core good is positive, consumers and service providers prefer single-till regulation while the monopoly prefers dual-till regulation. In a nutshell, under a positive profit from the non-core good, consumers and service providers prefer single-till regulation, whilst the monopoly prefers dual-till regulation; consumers and service providers have a totally opposite preference to the monopoly. Our result thus offers a formal demonstration of the regulatory practice showing that airports in general are strongly in favor of dual-till regulation, whilst airlines are strongly in favor of single-till regulation (e.g., Czerny et al., 2016a). Finally, the above results show that if a regulator implements dual-till regulation under a positive profit from the non-core good, then the regulator reveals its preference for the monopoly's profit, compared to consumers' utility or service providers' profit. This implies that the regulator is captured by the monopoly, because it can raise consumers' utility (or/and service providers profits) by adopting single-till regulation.

This study crucially depends on Kidokoro and Zhang (2022), but differs from it in at least two important aspects. First, we allow different welfare weights for the utility of consumers, service providers' profits, and the monopoly profit. This extension is significant not only in terms of practical relevance, because the regulator might not simply maximize their unweighted sum, but also in terms of new analytical results. By allowing different welfare weights, we can derive clear-cut results in certain specific cases, i.e., the regulator maximizes the utility of consumers, service providers' profits, or the monopoly profit. Second, we argue the relationship between a regulation type (single-till or dual-till) and regulatory capture. Regulatory capture theory asserts that "regulation is acquired by the industry and is designed and operated primarily for its benefit (Stigler (1971, p.3))."[2] We consider that the regulator is captured by service providers when it maximizes service providers' profit, and by the monopoly when it maximizes its profit. Single-till or dual-till regulation has been examined in a different context from regulatory capture theory,[3] and the relationship between regulatory capture and the choice of single-till or dual-till regulation has not been formally analyzed. Thus, our result is a relevant contribution in this aspect too.

[2] See, among others, Becker (1983), Dal Bó (2006), Djankov et al. (2002), and Peltzman (1976) for regulatory capture theory.

[3] See, among others, Beesley (1999), Crew and Kleindorfer (2000), Starkie (2001), Oum et al. (2004), Czerny et al. (2016a), Kidokoro et al. (2016), and Kidokoro and Zhang (2022).

The structure of the paper is as follows. Section 2 sets up the model. In Section 3, we derive results in the case of no congestion at the infrastructure/facility (e.g., airport); whereas in Section 4, we take the congestion into account. Section 5 shows the result of numerical examples. Section 6 concludes the analysis and discusses areas of further research.

## 2. Model

We consider a simple two-good model, which consists of a core good and a non-core good, based on Kidokoro and Zhang (2022). In the airport literature, the core good corresponds to the aeronautical service of an airport and the non-core good is the non-aeronautical service the airport offers, such as airport parking or a shopping mall (e.g., Zhang and Zhang, 1997; Starkie, 2001, 2021; Czerny, 2006; D'Alfonso et al., 2013; Nerja and Sanchez, 2021). We model consumers, service providers, and an infrastructure monopoly that correspond, in the airport context, to passengers, airlines, and an airport, respectively. Service providers (airlines) buy the core good as an input from the monopoly (airport), and then sell its output to the final consumers (passengers) in a "vertical structure" (Basso, 2008; Basso and Zhang, 2008a; Barbot et al., 2013; D'Alfonso and Nastasi, 2014).

Consider the representative consumer, who solves a utility-maximization problem formulated as

$$\begin{aligned}&\text{Max } U = z + u(x_1, x_2),\\ &\text{subject to } z + \tilde{p}_1 x_1 + p_2 x_2 = I\end{aligned} \tag{1}$$

where $z$, $x_1$, $x_2$, and $I$ are, respectively, the quantity of the numeraire good (and its price is normalized at unity), the demand for the good that uses the core good as input, the demand for the non-core good, and the income. Further, $\tilde{p}_1$ and $p_2$ denote the prices of $x_1$ and $x_2$ respectively. For the sake of analytical simplicity, the utility function is assumed to be quasi-linear with

$$\frac{\partial^2 u}{\partial x_1^2} < 0, \frac{\partial^2 u}{\partial x_2^2} < 0, \text{ and } \frac{\partial^2 u}{\partial x_1^2}\frac{\partial^2 u}{\partial x_2^2} - \left(\frac{\partial^2 u}{\partial x_1 \partial x_2}\right)^2 > 0 \tag{2}$$

so that $u(x_1, x_2)$ is strictly concave. Consumers simultaneously choose $x_1$ and $x_2$, being fully aware of the own- and cross-price effects. With the (non-zero) cross-price effect, this corresponds to the general case of "foresighted passengers" in the airport literature (e.g., Czerny, 2006; Flores-Fillol et al., 2018; Czerny and Zhang, 2020; D'Amico, 2022).[4] We assume that the demands for the core and non-core goods are complementary.

The utility-maximization by the representative consumer yields

$$\tilde{p}_1 = \frac{\partial u(x_1, x_2)}{\partial x_1}, \tag{3}$$

$$p_2 = \frac{\partial u(x_1, x_2)}{\partial x_2}. \tag{4}$$

Solving (3) and (4), we obtain $x_1(\tilde{p}_1, p_2)$ and $x_2(\tilde{p}_1, p_2)$. From $x_1(\tilde{p}_1, p_2)$, we can derive $\tilde{p}_1(x_1, p_2)$ which shows that the price of the core good in general depends on the non-core price.

Service providers produce one-unit final good, using one-unit core good as input. This implies that the demand for the final good that uses the core good as input always equals the demand for the core good. For

[4] A related notion in the literature is the airport being a two-sided market (Ivaldi et al., 2015; Wan and Zou, 2020; Starkie, 2021). In either case, it is possible that the pricing of non-aeronautical (aeronautical, respectively) services can affect the passenger travel demand (the non-aeronautical demand, respectively). For instance, Czerny et al. (2016b) demonstrate, empirically, that an increase in airport car rental prices reduces the passenger travel demand.

instance, in the airport context, service providers correspond to airlines. Service providers pay $p_1$ per one-unit core good. For the moment, we assume that service providers' supply costs are zero (We model service providers' costs in Section 4 where congestion costs are taken into account.). We assume that service providers are subject to imperfect competition,[5] and that they engage in Cournot (output) competition.[6] There are $N$ service providers, and the profit of provider $j$, $\pi_j^S$, is

$$\pi_j^S = (\widetilde{p}_1(x_1, p_2) - p_1)x_{1j} \tag{5}$$

where $x_{1j}$ is the output of service provider $j$, and $\sum_{j=1}^{N} x_{1j} = x_1$. Profit maximization by provider $j$ yields

$$\frac{\partial \pi_j^S}{\partial x_{1j}} = \widetilde{p}_1(x_1, p_2) - p_1 + \frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1}\frac{dx_1}{dx_{1j}}x_{1j} = 0 \tag{6}$$

from which we obtain

$$\widetilde{p}_1(x_1, p_2) = p_1 - \frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1}\frac{x_1}{N}. \tag{7}$$

We show

$$\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1} < 0 \tag{8}$$

in Appendix B (as part of the proof of Proposition 3, utilizing (2) of the quasi-linear utility function). We shall assume

$$\frac{\partial^2 \widetilde{p}_1(x_1, p_2)}{\partial {x_1}^2} < 0 \tag{9}$$

which is sufficient for the second-order conditions being satisfied. From (8), we have

$$-\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1}\frac{x_1}{N} > 0 \tag{10}$$

which shows an increase in price due to imperfect completion (as expected). Thus, from (7) and (10), we derive

$$\widetilde{p}_1(x_1, p_2) \rangle p_1. \tag{11}$$

Solving (3), (4), and (7) yields $\widetilde{p}_1(p_1, p_2)$, $x_1(p_1, p_2)$, and $x_2(p_1, p_2)$.

The monopoly provides its core good to the service providers and its non-core good to the (final) consumers. Its core and non-core profits are, respectively

$$\Pi^{MC} = p_1 x_1(p_1, p_2) - c_1(x_1(p_1, p_2)), \tag{12}$$

$$\Pi^{MNC} = p_2 x_2(p_1, p_2) - c_2(x_2(p_1, p_2)) \tag{13}$$

where $c_1(x_1(p_1, p_2))$ and $c_2(x_2(p_1, p_2))$ are, respectively, the production costs of the core and non-core goods. We assume that the marginal costs of the core and non-core goods are positive. Combining the core and non-core profits, the profit of the monopoly is

$$\begin{aligned}\Pi^M &= \Pi^{MC} + \Pi^{MNC} \\ &= p_1 x_1(p_1, p_2) - c_1(x_1(p_1, p_2)) + p_2 x_2(p_1, p_2) - c_2(x_2(p_1, p_2)).\end{aligned} \tag{14}$$

We assume that the participation constraint,

$$\Pi^M \geq 0 \tag{15}$$

is satisfied under single-till or dual-till regulation in order that the monopoly can operate.

We set the weights in social welfare ($SW$ below) for consumers' utility, the profit of service providers, the monopoly's profit from the core good, and the monopoly's profit from the non-core good at $\alpha_1$, $\alpha_2$, $\alpha_3$, and $\alpha_4$, respectively.[7] From (1), (5), (12), and (13), social welfare can then be written as

$$SW = \alpha_1 U + \alpha_2 \sum_{j=1}^{N} \pi_j^S + \alpha_3 \Pi^{MC} + \alpha_4 \Pi^{MNC}. \tag{16}$$

The main difference in the model from Kidokoro and Zhang (2022) is that we allow any weights for $\alpha_1$, $\alpha_2$, $\alpha_3$, and $\alpha_4$ in (16).[8] Note that Kidokoro and Zhang (2022) have implicitly assumed that all these welfare weights are the same and equal to unity.

As a useful analytical tool we introduce the following regulatory profit function

$$\begin{aligned}Reg(p_1, p_2) \equiv \Pi^{MC} + \beta \Pi^{MNC} = p_1 x_1(p_1, p_2) - c_1(x_1(p_1, p_2)) \\ + \beta(p_2 x_2(p_1, p_2) - c_2(x_2(p_1, p_2)))\end{aligned} \tag{17}$$

where $\beta$ may represent the degree of single-till regulation (relative to dual-till regulation). $Reg(p_1, p_2)$ is reduced to the combined profits when $\beta = 1$, i.e., single-till regulation; whilst it is reduced to the profit of the core good when $\beta = 0$, i.e., dual-till regulation. In order to analyze the welfare effect of switching from dual-till to single-till regulation, we shall treat $\beta$ as a continuous variable between 0 and 1. Because we consider social welfare maximization under regulation, the maximized welfare depends on $\beta$. We assume that $\frac{dSW}{d\beta}$ has the same sign in the range $0 \leq \beta \leq 1$. We will illustrate what happens if this assumption does not hold in Section 5. Using (17), we denote the value of regulatory profit under social welfare maximization without regulation by $Reg({p_1}^*, {p_2}^*)$, where the superscript $*$ denotes the values in the case of social welfare maximization throughout the paper.

Following Kidokoro and Zhang (2022), we have the two cases to analyze. First, consider the case of $Reg({p_1}^*, {p_2}^*) > 0$. Because the regulatory profit under welfare maximization is positive, the relevant regulatory purpose is to limit the regulatory profit to no larger than zero.[9] Thus, the maximization problem to be solved is

$$\text{Max } SW, \text{subject to } Reg(p_1, p_2) \leq 0 \text{ and } \Pi^M \geq 0. \tag{18}$$

Second, consider the case of $Reg({p_1}^*, {p_2}^*) < 0$. Because the regulatory profit under welfare maximization is negative, the relevant regulatory purpose is to increase the regulatory profit to no smaller than zero, i.e., to attain self-financing at least. Thus, the maximization problem to be solved is

$$\text{Max } SW, \text{subject to } Reg(p_1, p_2) \geq 0 \text{ and } \Pi^M \geq 0. \tag{19}$$

By solving (18) and (19), we have the following propositions.

**Proposition 1.** *When $Reg({p_1}^*, {p_2}^*) > 0$, dual-till regulation yields higher social welfare than single-till regulation, if the profit from the non-core good is*

[5] In the case of perfect competition, service providers play no active role in the present analysis.

[6] The assumption of Cournot competition among air carriers appears a standard modelling practice in the recent literature on airport pricing, capacity investment, and economic regulation. See, e.g., the survey paper by Zhang and Czerny (2012).

[7] We include the possibility that the regulator treats the monopoly's profits from the core good and from the non-core good differently, i.e., $\alpha_3$ and $\alpha_4$ can be different. In the airport setting, the regulator might not evaluate non-aeronautical profits with the same weight as the one for aeronautical profits.

[8] Ross (1984) illustrates how the regulator's welfare weights can be inferred from the actual data.

[9] Kidokoro and Zhang (2022) formulate the maximization problem including the regulatory waste in the same way as Braeutigam and Panzar (1989). If we allow various weights for $\alpha_1$, $\alpha_2$, $\alpha_3$, and $\alpha_4$ in (16), it is possible that the regulatory waste is positive. To avoid this case, we here assume that the regulatory waste is zero and the regulatory constraint is formulated as $Reg(p_1, p_2) \leq 0$ in (18) and $Reg(p_1, p_2) \geq 0$ in (19). However, even if we allow a positive regulatory waste, the following analysis holds without modification.

*positive. The two types of regulation are equivalent in terms of welfare if the profit from the non-core good is zero.*

**Proposition 2**. *When $Reg(p_1{}^*, p_2{}^*) < 0$, single-till regulation yields higher social welfare than dual-till regulation, if the profit from the non-core good is positive. The two types of regulation are equivalent in terms of welfare if the profit from the non-core good is zero.*

*The proof is given in Appendix A. Propositions 1 and 2 demonstrate that the weights in social welfare for consumers' utility, the profit of service providers, and the monopoly's profit have no effect on Propositions 1 and 2 of Kidokoro and Zhang (2022). A slightly different point from Kidokoro and Zhang (2022) is that the participation constraint makes it impossible to compare single-till and dual-till regulation when the profit from the non-core good is negative. The profit of the monopoly can be rewritten as*

$$\begin{aligned}\Pi^M &= \Pi^{MC} + \Pi^{MNC} = \Pi^{MC} + \beta\Pi^{MNC} + (1-\beta)\Pi^{MNC} \\ &= Reg(p_1, p_2) + (1-\beta)\Pi^{MNC}.\end{aligned} \tag{20}$$

*Suppose that the regulation is binding, i.e., $Reg(p_1, p_2) = 0$. When the profit from the non-core good, $\Pi^{MNC}$, is negative, $\beta = 1$ is required for the participation constraint to be satisfied. That is, $\Pi^M = 0$ for $\beta = 1$ but $\Pi^M < 0$ for $0 \le \beta < 1$. Thus, the only case in which the participation constraint is satisfied is single-till regulation.*

## 3. Effects of welfare weights

Propositions 1 and 2 are general results that hold for any values of $\alpha_1$, $\alpha_2$, $\alpha_3$, and $\alpha_4$. We further derive interesting results for certain special values of welfare weights.

### 3.1. When the regulator maximizes consumers' utility

We first consider the case in which social welfare corresponds to consumers' utility: that is, the regulator maximizes consumers' utility, not taking into account of the profits of service providers and the monopoly. In this case, the welfare weights are $\alpha_1 = 1$ and $\alpha_2 = \alpha_3 = \alpha_4 = 0$. We obtain the following proposition.

**Proposition 3**. *When the regulator maximizes consumers' utility, single-till regulation yields higher welfare than dual-till regulation if the profit from the non-core good is positive. The two types of regulation are equivalent in terms of welfare if the profit from the non-core good is zero.*

*The proof is given in Appendix B. The basic intuition behind Proposition 3 is as follows. When welfare is given by consumers' utility, lowering the prices of the core and non-core goods make consumers' utility higher; consequently, their optimal prices are zero. Thus, we have $Reg(p_1{}^*, p_2{}^*) < 0$ and the result of Proposition 2 is applicable. That is, single-till regulation is superior to dual-till regulation if the profit from the non-core good is positive. In the context of airport regulation, if the profit from non-aeronautical services is positive, lower airport charges that are cross-subsidized by the non-aeronautical profit are desirable for passengers (consumers). The result of Proposition 3 suggests that single-till regulation is superior from the viewpoint of consumers.*

### 3.2. When the regulator is captured by service providers or the monopoly

As mentioned in the introduction, we consider that the regulator is captured by service providers when it maximizes service providers' profit, and by the monopoly when it maximizes its profit. In our airport example, the former case corresponds to the regulatory capture by airlines,[10] while the latter to the regulatory capture by an airport.

[10] Li et al. (2019) empirically test regulatory capture by airlines in China's airfare deregulation. They show that public interest, not regulatory capture, is a driving force in deregulation.

#### 3.2.1. When the regulator maximizes service providers' profit

When the regulator maximizes service providers' profit, not taking into account of consumers' utility and the monopoly's profit, the weights are $\alpha_2 = 1$ and $\alpha_1 = \alpha_3 = \alpha_4 = 0$. We obtain the following results.

**Proposition 4**. *When the regulator maximizes the profit of service providers, single-till regulation yields higher welfare than dual-till regulation if the profit from the non-core good is positive. The two types of regulation are equivalent in terms of welfare if the profit from the non-core good is zero.*

*The proof is shown in Appendix C. The results can also be understood intuitively. When welfare equals the profit of service providers, a lower price of the core good makes the profit of service providers higher by lowering their costs. A lower price of the non-core good makes the demand of the core good higher due to the complementary relationship between the two goods, which leads to a higher profit for service providers. These mechanisms imply that the optimal prices of the core and non-core goods for service providers are zero. Consequently, we have $Reg(p_1{}^*, p_2{}^*) < 0$ and the result of Proposition 2 is then applicable. That is, single-till regulation is superior to dual-till regulation if the profit of the non-core good is positive. In the context of airport regulation, if the profit from non-aeronautical services is positive, lower airport charges that are cross-subsidized by the non-aeronautical profit are desirable for airlines (see also Czerny et al., 2016a). The result of Proposition 4 suggests that single-till regulation is superior from the viewpoint of service providers (airlines).*

#### 3.2.2. When the regulator maximizes the weighted sum of consumers' utility and service providers' profit

We have treated the case in which welfare equals consumers' utility in Proposition 3, and the case in which welfare equals the profit of service providers in Proposition 4. Both propositions demonstrate that single-till regulation outperforms dual-till regulation as long as the profit from the non-core good is positive. Combining Propositions 3 and 4 we obtain the following Corollary 1, when social welfare equals the weighted sum of consumers' utility and the profit of service providers, i.e., $\alpha_1 > 0$, $\alpha_2 > 0$, and $\alpha_3 = \alpha_4 = 0$.

**Corollary 1**. *When the regulator maximizes the weighted sum of consumers' utility and service providers' profit, single-till regulation yields higher welfare than dual-till regulation if the profit from the non-core good is positive. The two types of regulation are equivalent in terms of welfare if the profit from the non-core good is zero.*

*The proof is shown in Appendix D. Corollary 1 shows that single-till regulation is desirable with any weights for consumers' utility and service providers' profit, as long as the profit from the non-core good is positive. Both are the users of the infrastructure monopoly: Service providers are direct users of the core good, and consumers are the indirect users who buy the core good through service providers. Corollary 1 states that single-till regulation is preferred by the users of the monopoly's core good when the profit from the non-core good is positive.*

#### 3.2.3. When the regulator maximizes the monopoly's profit

We now consider the case in which the regulator maximizes the profit of the monopoly, not taking into account of both consumers' utility and service providers' profit. In this case, the weights are $\alpha_1 = \alpha_2 = 0$, $\alpha_3 > 0$, and $\alpha_4 > 0$. We obtain the following proposition.

**Proposition 5**. *When the regulator maximizes the profit of the monopoly, dual-till regulation yields higher welfare than dual-till regulation, if the profit from the non-core good is positive. The two types of regulation are equivalent in terms of welfare if the profit from the non-core good is zero.*

*The proof is shown in Appendix E. When social welfare is given by the monopoly's profit, it is larger when the positive profit from the non-core good is unregulated. Consequently, if the profit from the non-core good is positive, consumers and service providers prefer single-till regulation while the monopoly prefers dual-till regulation. That is, consumers and service providers* *have the opposite preference to the monopoly regarding the form of the regulation. Our result offers a formal demonstration of the argument by* Czerny et al. (2016a, p.363), *that "… regulatory practice shows that airports in general are strongly in favor of dual-till regulation, while airlines are strongly in favor of single-till regulation."*

### *3.3. Implications for regulatory capture*

The above results show that if a regulator implements dual-till regulation under a positive profit from the non-core good, then the regulator reveals its preference for the monopoly's profit, relative to consumers' utility or service providers' profit. This implies that the regulator is captured by the monopoly (e.g., airport) because it can raise consumers' utility (or/and service providers profits) by adopting single-till regulation, instead of dual-till regulation. On the other hand, when a regulator is captured by service providers (e.g., airlines), a regulator will choose single-till regulation. Because this is the same result under consumers' utility maximization, we cannot tell whether a regulator implements single-till regulation for consumers (e.g., passengers) or service providers. That is, dual-till regulation under a positive profit from non-aeronautical services may be a sign of regulatory capture by an airport, while single-till regulation under a positive non-aeronautical profit may not reveal a sign of regulatory capture by airlines.

In practice, the situation can be complex and the regulatory capture by both airports and airlines is possible. For example, in Japan, All Nippon Airlines (ANA) and Japan Airlines (JAL) have historically accepted ex-bureaucrats from the regulator, the Ministry of Land, Infrastructure, Transport and Tourism, into their groups. Japan Airport Terminal, which is mainly operating Haneda Airport passenger terminals, has hired both ex-bureaucrats from the regulator and ex-airline employees from ANA and JAL.

## 4. Effects of infrastructure congestion

The analysis in Section 3 pays no attention to congestion that the infrastructure monopoly may face (for general discussion and literature on airport congestion and pricing issues see, among others, Basso and Zhang, 2008b, Zhang and Czerny, 2012, and Gillen et al., 2016). In this section, we explicitly consider this infrastructure congestion. Kidokoro and Zhang (2022) demonstrate that Proposition 1 is more likely to hold when congestion exists in the core good, because congestion tends to make the price of the core good higher. This mechanism is general and remains to hold in the present situation. For special cases we have considered (i.e., social welfare is equal to consumers' utility, the profit of service providers, the weighted sum of the two, and the profit of the monopoly), our derived results of Propositions 3, 4, and 5 and Corollary 1 continue to hold without modification. We then conclude that the (potential) infrastructure congestion has no effect on our argument. In effect, we have modified the model to incorporate congestion in Appendix F and proved Propositions 3, 4, and 5 and Corollary 1 in Appendices G, H, J, and I, respectively.

## 5. Numerical examples

We further illustrate our results by numerical examples, in which we use the following simple functional forms and parameters

$$U = -\frac{1}{2}{x_1}^2 - \frac{1}{2}{x_2}^2 + 100x_1 + 100x_2 + \frac{1}{2}x_1x_2,$$
$$I = 10,$$
$$c_1 = 10x_1 + 100,$$
$$c_2 = 10{x_2}^2,$$
$$N = 5.$$

We include the fixed cost for the core good, considering that real regulated industries are typically subject to increasing returns in the case of no congestion. On the contrary, for the non-core good, we use a normal decreasing-return cost function.

The results are shown in Tables 1–7 and A-1 to A-7. In all the tables, Case 1 shows the result of unconstrained social welfare maximization, while Case 2 shows the result of social welfare maximization under regulation. $mc_1$, $mc_2$, $\Pi^S \equiv \sum_{j=1}^{N}\pi_j^S$, $SW^{UW}$, $Reg^* \equiv Reg({p_1}^*, {p_2}^*)$ respectively are the marginal cost of the core good, the marginal cost of the non-core good, the aggregated profits of service providers, the unweighted sum of consumers' utility, service providers' profit, and a monopoly's profit, and the regulatory profit under unconstrained social welfare maximization. In Case 2, the italic letters illustrate that the aggregated profits of the core and non-core goods for a monopoly are negative, and consequently, the participation constraint is not satisfied, while the bold letters show the case in which maximum social welfare is attained. The numbers after the decimal point are suppressed to save the space, when the numbers are negative and large in absolute value.

### *5.1. When welfare equals consumers' utility, service providers' profit, or the monopoly's profit*

Our numerical examples successfully illustrate theoretical results when welfare equals consumers' utility, service providers' profit, or the monopoly's profit.

First, Table 1 shows the result in which social welfare equals consumers' utility. When $\beta = 0$ in Case 2, i.e., the simple dual-till regulation is imposed, the price of the non-core good is zero, and the aggregated profits of the core and non-core goods for a monopoly are negative. The regulated firm cannot operate in this case, that is, the participation constraint is not satisfied, and consequently, we exclude this case. In the range of $\beta = [0.1, 1.0]$, $\beta = 1.0$, i.e., the simple single-till regulation attains the highest social welfare. This corresponds to the case of Proposition 3 under the positive non-core profit.

Second, Table 2 shows the results in which social welfare equals the profit of service providers. The participation constraint is not satisfied in the range of $\beta = [0, 0.2]$ in Table 2. Except for this, the same trend as Table 1 holds, thus confirming Proposition 4.

Third, Table 3 shows the results in which social welfare equals the profit of the regulated monopoly. We exclude the case of $\beta = 1.0$, because the model degenerates,[11] as implied by Braeutigam and Panzar (1989). As Proposition 5 implies, dual-till regulation is best under the positive profit from the non-core good.

### *5.2. When welfare equals the unweighted sum of consumers' utility, service providers' profit, and the monopoly's profit*

If social welfare equals consumers' utility, the profit of service providers, or their weighted sum, single-till regulation attains higher welfare under the positive profit from the non-core good. On the contrary, if social welfare equals the profit of the regulated monopoly, dual-till regulation attains higher welfare. When welfare equals the unweighted sum of consumers' utility, service providers' profit, and the regulated monopoly's profit, the result depends on which effect is stronger. We check this point in Tables 4 and 5.

In Table 4, the former effect is stronger, and consequently, a simple single-till regulation of $\beta = 1.0$ yields the highest welfare. In Table 5, we consider more competitive service providers and change $N = 5$ to $N = 100$. In this case, the highest social welfare is attained under $\beta = 0.3$, which corresponds to the hybrid of single-till and dual-till regulation. When service providers are more competitive, the price of the final good that use the core good as input, $\tilde{p}_1$, decreases. The regulator can instead approve a higher price for the non-core good, and the price of the non-

[11] The regulated monopoly gains zero profit whatever behavior it takes, and consequently, any combination of $p_1$ and $p_2$ is possible as long as it satisfies the regulatory constraint.

**Table 1**
When social welfare equals consumer's utility.

| | Case 1 | Case 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0 | *0* | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | **1.0** |
| $p_1$ | 0.00 | *10.65* | 10.69 | 10.13 | 9.57 | 9.02 | 8.46 | 7.92 | 7.37 | 6.82 | 6.28 | **5.74** |
| $\widetilde{p}_1$ | 25.00 | *33.87* | 22.76 | 22.27 | 21.78 | 21.30 | 20.82 | 20.34 | 19.87 | 19.40 | 18.93 | **18.46** |
| $p_2$ | 0.00 | *0.00* | 133.76 | 134.08 | 134.33 | 134.57 | 134.81 | 135.04 | 135.27 | 135.50 | 135.73 | **135.95** |
| $mc_1$ | 10.00 | *10.00* | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | **10.00** |
| $mc_2$ | 3666.67 | *3548.38* | 129.56 | 127.69 | 127.44 | 127.46 | 127.57 | 127.72 | 127.89 | 128.08 | 128.27 | **128.47** |
| $x_1$ | 166.67 | *154.84* | 80.48 | 80.93 | 81.41 | 81.89 | 82.37 | 82.85 | 83.33 | 83.81 | 84.28 | **84.75** |
| $x_2$ | 183.33 | *177.42* | 6.48 | 6.38 | 6.37 | 6.37 | 6.38 | 6.39 | 6.39 | 6.40 | 6.41 | **6.42** |
| $U$ | 15426.67 | *14000.55* | 3008.80 | 3046.54 | 3084.33 | 3122.15 | 3160.02 | 3197.94 | 3235.89 | 3273.90 | 3311.96 | **3350.06** |
| $\Pi^S$ | 4166.67 | *3596.22* | 971.55 | 982.35 | 994.02 | 1005.83 | 1017.71 | 1029.63 | 1041.56 | 1053.52 | 1065.50 | **1077.49** |
| $\Pi^{MC}$ | −1766.67 | *0.00* | −44.69 | −89.68 | −134.98 | −180.59 | −226.50 | −272.73 | −319.26 | −366.10 | −413.24 | **−460.68** |
| $\Pi^{MNC}$ | −336111 | *−314775* | 446.86 | 448.41 | 449.93 | 451.47 | 453.01 | 454.55 | 456.09 | 457.62 | 459.16 | **460.68** |
| $\Pi^M$ | −337878 | *−314775* | 402.18 | 358.72 | 314.95 | 270.88 | 226.50 | 181.82 | 136.83 | 91.52 | 45.92 | **0.00** |
| $SW$ | 15426.67 | *14000.55* | 3008.80 | 3046.54 | 3084.33 | 3122.15 | 3160.02 | 3197.94 | 3235.89 | 3273.90 | 3311.96 | **3350.06** |
| $SW^{UW}$ | −318284 | *−297178* | 4382.53 | 4387.62 | 4393.30 | 4398.87 | 4404.24 | 4409.38 | 4414.28 | 4418.95 | 4423.37 | **4427.56** |
| $Reg^*$ | −337878 | *−1767* | −35378 | −68989 | −102600 | −136211 | −169822 | −203433 | −237044 | −270656 | −304267 | **−337878** |

**Table 2**
When social welfare equals service providers' profit.

| | Case 1 | Case 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0 | *0* | *0.1* | *0.2* | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | **1.0** |
| $p_1$ | 0.00 | *10.65* | *15.45* | *12.47* | 11.13 | 10.19 | 9.41 | 8.71 | 8.05 | 7.43 | 6.82 | **6.23** |
| $\widetilde{p}_1$ | 25.00 | *33.87* | *28.16* | *24.92* | 23.55 | 22.63 | 21.89 | 21.24 | 20.64 | 20.08 | 19.54 | **19.01** |
| $p_2$ | 0.00 | *0.00* | *116.63* | *125.64* | 128.70 | 130.33 | 131.39 | 132.17 | 132.79 | 133.32 | 133.77 | **134.18** |
| $mc_1$ | 10.00 | *10.00* | *10.00* | *10.00* | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | **10.00** |
| $mc_2$ | 3666.67 | *3548.38* | *514.44* | *317.31* | 254.00 | 222.86 | 204.39 | 192.20 | 183.58 | 177.18 | 172.25 | **168.36** |
| $x_1$ | 166.67 | *154.84* | *84.71* | *83.01* | 82.80 | 82.94 | 83.22 | 83.56 | 83.94 | 84.35 | 84.77 | **85.20** |
| $x_2$ | 183.33 | *177.42* | *25.72* | *15.87* | 12.70 | 11.14 | 10.22 | 9.61 | 9.18 | 8.86 | 8.61 | **8.42** |
| $U$ | 15426.67 | *14000.55* | *2838.92* | *2923.00* | 2992.82 | 3049.53 | 3099.62 | 3146.04 | 3190.25 | 3233.04 | 3274.87 | **3316.04** |
| $\Pi^S$ | 4166.67 | *3596.22* | *1076.25* | *1033.70* | 1028.39 | 1031.86 | 1038.79 | 1047.41 | 1057.01 | 1067.23 | 1077.85 | **1088.76** |
| $\Pi^{MC}$ | −1766.67 | *0.00* | *361.62* | *104.76* | −6.48 | −84.23 | −149.18 | −207.99 | −263.47 | −316.99 | −369.32 | **−420.90** |
| $\Pi^{MNC}$ | −336111 | *−314775* | *−3616.16* | *−523.79* | 21.59 | 210.57 | 298.36 | 346.66 | 376.38 | 396.24 | 410.35 | **420.90** |
| $\Pi^M$ | −337878 | *−314775* | *−3254.54* | *−419.03* | 15.11 | 126.34 | 149.18 | 138.66 | 112.92 | 79.25 | 41.04 | **0.00** |
| $SW$ | 4166.67 | *3596.22* | *1076.25* | *1033.70* | 1028.39 | 1031.86 | 1038.79 | 1047.41 | 1057.01 | 1067.23 | 1077.85 | **1088.76** |
| $SW^{UW}$ | −318284 | *−297178* | *660.63* | *3537.67* | 4036.32 | 4207.74 | 4287.58 | 4332.11 | 4360.18 | 4379.51 | 4393.75 | **4404.79** |
| $Reg^*$ | −337878 | *−1767* | *−35378* | *−68989* | −102600 | −136211 | −169822 | −203433 | −237044 | −270656 | −304267 | **−337878** |

**Table 3**
When social welfare equals a monopoly's profit.

| | Case 1 | Case 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0 | **0** | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| $p_1$ | 55.00 | **11.25** | 10.69 | 10.13 | 9.57 | 9.02 | 8.46 | 7.92 | 7.37 | 6.83 | 6.28 | 35.05 |
| $\widetilde{p}_1$ | 61.29 | **23.25** | 22.76 | 22.27 | 21.79 | 21.31 | 20.83 | 20.35 | 19.88 | 19.40 | 18.93 | 44.77 |
| $p_2$ | 114.52 | **133.56** | 133.79 | 134.03 | 134.26 | 134.49 | 134.73 | 134.96 | 135.19 | 135.41 | 135.64 | 113.18 |
| $mc_1$ | 10.00 | **10.00** | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| $mc_2$ | 129.03 | **128.55** | 128.76 | 128.98 | 129.20 | 129.42 | 129.63 | 129.84 | 130.06 | 130.27 | 130.48 | 384.80 |
| $x_1$ | 41.94 | **79.97** | 80.46 | 80.95 | 81.44 | 81.93 | 82.41 | 82.90 | 83.38 | 83.85 | 84.33 | 64.85 |
| $x_2$ | 6.45 | **6.43** | 6.44 | 6.45 | 6.46 | 6.47 | 6.48 | 6.49 | 6.50 | 6.51 | 6.52 | 19.24 |
| $U$ | 774.83 | **2971.10** | 3008.80 | 3046.54 | 3084.31 | 3122.12 | 3159.98 | 3197.88 | 3235.83 | 3273.82 | 3311.86 | 1673.81 |
| $\Pi^S$ | 263.79 | **959.23** | 971.13 | 983.03 | 994.95 | 1006.88 | 1018.82 | 1030.77 | 1042.73 | 1054.71 | 1066.70 | 630.77 |
| $\Pi^{MC}$ | 1787.10 | **0.00** | −44.69 | −89.69 | −135.00 | −180.63 | −226.56 | −272.80 | −319.35 | −366.21 | −413.36 | 1524.17 |
| $\Pi^{MNC}$ | 322.58 | **445.31** | 446.88 | 448.45 | 450.01 | 451.57 | 453.13 | 454.67 | 456.22 | 457.76 | 459.29 | −1524.17 |
| $\Pi^M$ | 2109.68 | **445.31** | 402.19 | 358.76 | 315.01 | 270.94 | 226.56 | 181.87 | 136.87 | 91.55 | 45.93 | 0.00 |
| $SW$ | 2109.68 | **445.31** | 402.19 | 358.76 | 315.01 | 270.94 | 226.56 | 181.87 | 136.87 | 91.55 | 45.93 | 0.00 |
| $SW^{UW}$ | 3148.29 | **4375.64** | 4382.12 | 4388.33 | 4394.27 | 4399.95 | 4405.36 | 4410.52 | 4415.42 | 4420.08 | 4424.49 | 2304.58 |
| $Reg^*$ | 2109.68 | **1787.10** | 1819.35 | 1851.61 | 1883.87 | 1916.13 | 1948.39 | 1980.65 | 2012.90 | 2045.16 | 2077.42 | 2109.68 |

core good increases. This makes the profit from the non-core good larger, and also makes the aggregated profit of the core and non-core good larger. In this case, the regulated monopoly's profit is more important in social welfare, and dual-till regulation is more desirable.

The result in Table 5 is also an example in which our assumption in Section 2 that $\frac{dSW}{d\beta}$ has the same sign in the range $0 \leq \beta \leq 1$ does not hold, because the regulatory profit under unconstrained welfare maximization, $Reg^*$, changes from negative to positive as $\beta$ is larger. When the assumption does not hold, it is possible that the hybrid form of single-till and dual-till regulation yields the highest social welfare.

Table 6 shows the results in which the regulator gives a lower weight for the profit from the non-core good at 0.5 when $N = 5$ and Table 7 does when $N = 100$. Because the weight is low, the profit from the non-core good is low. The relative importance of single-till regulation, in which the loss from the core good is cross-subsidized by the non-core profit, is also lower. In Table 6 of $N = 5$, single-till regulation still attains the

**Table 4**
When social welfare equals the unweighted sum of consumer's utility, service providers' profits, and a monopoly's profit.

| | Case 1 | Case 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0 | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | **1.0** |
| $p_1$ | 0.00 | 11.25 | 10.69 | 10.13 | 9.58 | 9.03 | 8.48 | 7.93 | 7.39 | 6.85 | 6.31 | **5.77** |
| $\tilde{p}_1$ | 13.50 | 23.28 | 22.79 | 22.31 | 21.83 | 21.35 | 20.87 | 20.39 | 19.92 | 19.45 | 18.98 | **18.51** |
| $p_2$ | 138.02 | 133.15 | 133.40 | 133.64 | 133.89 | 134.13 | 134.37 | 134.61 | 134.85 | 135.09 | 135.32 | **135.55** |
| $mc_1$ | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | **10.00** |
| $mc_2$ | 139.54 | 139.00 | 138.85 | 138.72 | 138.62 | 138.54 | 138.48 | 138.43 | 138.40 | 138.38 | 138.38 | **138.38** |
| $x_1$ | 89.99 | 80.20 | 80.68 | 81.16 | 81.64 | 82.12 | 82.59 | 83.07 | 83.54 | 84.01 | 84.48 | **84.95** |
| $x_2$ | 6.98 | 6.95 | 6.94 | 6.94 | 6.93 | 6.93 | 6.92 | 6.92 | 6.92 | 6.92 | 6.92 | **6.92** |
| $U$ | 3769.51 | 2971.35 | 3008.69 | 3046.11 | 3083.60 | 3121.16 | 3158.80 | 3196.50 | 3234.27 | 3272.10 | 3310.00 | **3347.96** |
| $\Pi^S$ | 1214.73 | 964.77 | 976.39 | 988.06 | 999.75 | 1011.47 | 1023.23 | 1035.00 | 1046.81 | 1058.64 | 1070.49 | **1082.37** |
| $\Pi^{MC}$ | −999.90 | 0.00 | −44.41 | −89.17 | −134.28 | −179.72 | −225.49 | −271.59 | −318.01 | −364.75 | −411.80 | **−459.17** |
| $\Pi^{MNC}$ | 476.17 | 442.36 | 444.13 | 445.87 | 447.59 | 449.30 | 450.98 | 452.64 | 454.29 | 455.93 | 457.56 | **459.17** |
| $\Pi^M$ | −523.73 | 442.36 | 399.72 | 356.70 | 313.32 | 269.58 | 225.49 | 181.06 | 136.29 | 91.19 | 45.76 | **0.00** |
| $SW$ | 4460.51 | 4378.48 | 4384.80 | 4390.86 | 4396.67 | 4402.21 | 4407.51 | 4412.56 | 4417.36 | 4421.93 | 4426.25 | **4430.34** |
| $SW^{UW}$ | 4460.51 | 4378.48 | 4384.80 | 4390.86 | 4396.67 | 4402.21 | 4407.51 | 4412.56 | 4417.36 | 4421.93 | 4426.25 | **4430.34** |
| $Reg^*$ | −523.73 | −999.90 | −952.28 | −904.67 | −857.05 | −809.43 | −761.82 | −714.20 | −666.58 | −618.97 | −571.35 | **−523.73** |

**Table 5**
When social welfare equals the unweighted sum of consumer's utility, service providers' profits, and a monopoly's profit and $N = 100$

| | Case 1 | Case 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0 | 0 | 0.1 | 0.2 | **0.3** | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| $p_1$ | 9.30 | 11.09 | 10.56 | 10.03 | **9.50** | 8.98 | 8.46 | 7.94 | 7.42 | 6.90 | 6.38 | 5.87 |
| $\tilde{p}_1$ | 10.00 | 11.78 | 11.25 | 10.73 | **10.20** | 9.68 | 9.16 | 8.65 | 8.13 | 7.62 | 7.11 | 6.60 |
| $p_2$ | 139.76 | 138.87 | 139.13 | 139.40 | **139.66** | 139.92 | 140.18 | 140.43 | 140.69 | 140.95 | 141.20 | 141.45 |
| $mc_1$ | 10.00 | 10.00 | 10.00 | 10.00 | **10.00** | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| $mc_2$ | 139.76 | 139.76 | 139.75 | 139.75 | **139.75** | 139.77 | 139.79 | 139.82 | 139.85 | 139.88 | 139.92 | 139.97 |
| $x_1$ | 93.49 | 91.72 | 92.24 | 92.77 | **93.29** | 93.81 | 94.33 | 94.85 | 95.36 | 95.88 | 96.39 | 96.90 |
| $x_2$ | 6.99 | 6.99 | 6.99 | 6.99 | **6.99** | 6.99 | 6.99 | 6.99 | 6.99 | 6.99 | 7.00 | 7.00 |
| $U$ | 4078.31 | 3919.86 | 3966.48 | 4013.20 | **4060.01** | 4106.92 | 4153.93 | 4201.03 | 4248.23 | 4295.52 | 4342.92 | 4390.41 |
| $\Pi^S$ | 65.56 | 63.09 | 63.82 | 64.54 | **65.27** | 66.00 | 66.74 | 67.47 | 68.21 | 68.95 | 69.68 | 70.42 |
| $\Pi^{MC}$ | −165.56 | 0.00 | −48.39 | −97.16 | **−146.28** | −195.77 | −245.61 | −295.82 | −346.38 | −397.29 | −448.55 | −500.17 |
| $\Pi^{MNC}$ | 488.31 | 482.10 | 483.95 | 485.78 | **487.60** | 489.42 | 491.23 | 493.03 | 494.82 | 496.61 | 498.39 | 500.17 |
| $\Pi^M$ | 322.76 | 482.10 | 435.55 | 388.62 | **341.32** | 293.65 | 245.61 | 197.21 | 148.45 | 99.32 | 49.84 | 0.00 |
| $SW$ | 4466.63 | 4465.05 | 4465.84 | 4466.36 | **4466.61** | 4466.58 | 4466.28 | 4465.71 | 4464.88 | 4463.79 | 4462.44 | 4460.84 |
| $SW^{UW}$ | 4466.63 | 4465.05 | 4465.84 | 4466.36 | **4466.61** | 4466.58 | 4466.28 | 4465.71 | 4464.88 | 4463.79 | 4462.44 | 4460.84 |
| $Reg^*$ | 322.76 | −165.56 | −116.73 | −67.90 | **−19.06** | 29.77 | 78.60 | 127.43 | 176.26 | 225.09 | 273.92 | 322.76 |

**Table 6**
When social welfare equals the unweighted sum of consumer's utility, service providers' profits, and a monopoly's profit with the weight for the non-core profit of 0.5

| | Case 1 | Case 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0 | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | **1.0** |
| $p_1$ | 0.00 | 11.24 | 10.70 | 10.15 | 9.61 | 9.06 | 8.52 | 7.98 | 7.44 | 6.90 | 6.37 | **5.83** |
| $\tilde{p}_1$ | 13.52 | 23.31 | 22.83 | 22.36 | 21.88 | 21.41 | 20.93 | 20.46 | 19.99 | 19.52 | 19.06 | **18.59** |
| $p_2$ | 137.74 | 132.71 | 132.98 | 133.24 | 133.50 | 133.75 | 134.01 | 134.26 | 134.51 | 134.75 | 134.99 | **135.23** |
| $mc_1$ | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | **10.00** |
| $mc_2$ | 146.54 | 150.30 | 149.52 | 148.85 | 148.27 | 147.77 | 147.33 | 146.95 | 146.62 | 146.34 | 146.11 | **145.91** |
| $x_1$ | 90.14 | 80.45 | 80.90 | 81.36 | 81.82 | 82.29 | 82.75 | 83.21 | 83.67 | 84.13 | 84.60 | **85.06** |
| $x_2$ | 7.33 | 7.51 | 7.48 | 7.44 | 7.41 | 7.39 | 7.37 | 7.35 | 7.33 | 7.32 | 7.31 | **7.30** |
| $U$ | 3769.41 | 2971.84 | 3008.28 | 3044.94 | 3081.80 | 3118.83 | 3156.00 | 3193.30 | 3230.72 | 3268.24 | 3305.86 | **3343.57** |
| $\Pi^S$ | 1218.84 | 970.77 | 981.83 | 993.01 | 1004.29 | 1015.65 | 1027.09 | 1038.60 | 1050.17 | 1061.79 | 1073.45 | **1085.16** |
| $\Pi^{MC}$ | −1001.42 | 0.00 | −43.52 | −87.54 | −132.03 | −176.94 | −222.26 | −267.96 | −314.03 | −360.46 | −407.24 | **−454.35** |
| $\Pi^{MNC}$ | 472.40 | 432.55 | 435.22 | 437.72 | 440.09 | 442.35 | 444.52 | 446.60 | 448.62 | 450.58 | 452.48 | **454.35** |
| $\Pi^M$ | −529.02 | 432.55 | 391.70 | 350.18 | 308.06 | 265.41 | 222.26 | 178.64 | 134.59 | 90.12 | 45.25 | **0.00** |
| $SW$ | 4223.03 | 4158.89 | 4164.19 | 4169.26 | 4174.11 | 4178.72 | 4183.10 | 4187.25 | 4191.17 | 4194.86 | 4198.32 | **4201.56** |
| $SW^{UW}$ | 4459.23 | 4375.16 | 4381.80 | 4388.13 | 4394.15 | 4399.89 | 4405.36 | 4410.55 | 4415.48 | 4420.15 | 4424.56 | **4428.73** |
| $Reg^*$ | −529.02 | −1001.42 | −954.18 | −906.94 | −859.70 | −812.46 | −765.22 | −717.98 | −670.74 | −623.50 | −576.26 | **−529.02** |

highest social welfare, as shown in Table 4. In Table 7 of $N = 100$, simple dual-till regulation, not the hybrid form of single-till and dual-till regulation shown in Table 5, attains the highest social welfare.

### *5.3. When congestion exists*

When congestion exists in the core good, the price of the core good is higher, and this makes consumers' utility lower. Thus, the importance of the monopoly's profit becomes relatively higher. The general trend is that dual-till regulation is more likely to dominate single-till regulation when social welfare includes the monopoly's profit. We explain the results in detail in Appendix K.

## 6. Concluding remarks

By applying Kidokoro and Zhang (2022)'s analysis, we have

**Table 7**
When social welfare equals the unweighted sum of consumer's utility, service providers' profits, and a monopoly's profit with the weight for the non-core profit of 0.5 and $N = 100$

| | Case 1 | Case 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0 | **0** | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| $p_1$ | 11.14 | **11.09** | 10.56 | 10.04 | 9.51 | 8.99 | 8.47 | 7.95 | 7.43 | 6.92 | 6.40 | 5.89 |
| $\tilde{p}_1$ | 11.82 | **11.78** | 11.25 | 10.73 | 10.21 | 9.69 | 9.18 | 8.66 | 8.15 | 7.64 | 7.13 | 6.62 |
| $p_2$ | 138.62 | **138.64** | 138.91 | 139.18 | 139.45 | 139.71 | 139.98 | 140.24 | 140.50 | 140.76 | 141.02 | 141.27 |
| $mc_1$ | 10.00 | **10.00** | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| $mc_2$ | 145.91 | **145.89** | 145.64 | 145.43 | 145.24 | 145.08 | 144.94 | 144.82 | 144.71 | 144.62 | 144.54 | 144.47 |
| $x_1$ | 91.82 | **91.87** | 92.39 | 92.90 | 93.42 | 93.93 | 94.45 | 94.96 | 95.47 | 95.98 | 96.49 | 96.99 |
| $x_2$ | 7.30 | **7.29** | 7.28 | 7.27 | 7.26 | 7.25 | 7.25 | 7.24 | 7.24 | 7.23 | 7.23 | 7.22 |
| $U$ | 3917.47 | **3921.56** | 3967.78 | 4014.15 | 4060.66 | 4107.31 | 4154.08 | 4200.98 | 4248.00 | 4295.14 | 4342.40 | 4389.77 |
| $\Pi^S$ | 63.24 | **63.30** | 64.01 | 64.73 | 65.45 | 66.18 | 66.90 | 67.63 | 68.36 | 69.09 | 69.82 | 70.56 |
| $\Pi^{MC}$ | 4.24 | **0.00** | −48.13 | −96.66 | −145.59 | −194.91 | −244.61 | −294.69 | −345.14 | −395.96 | −447.15 | −498.70 |
| $\Pi^{MNC}$ | 479.03 | **479.22** | 481.28 | 483.30 | 485.30 | 487.27 | 489.22 | 491.15 | 493.06 | 494.95 | 496.83 | 498.70 |
| $\Pi^M$ | 483.27 | **479.21** | 433.15 | 386.64 | 339.71 | 292.36 | 244.61 | 196.46 | 147.92 | 98.99 | 49.68 | 0.00 |
| $SW$ | 4224.47 | **4224.46** | 4224.30 | 4223.87 | 4223.18 | 4222.21 | 4220.98 | 4219.49 | 4217.75 | 4215.74 | 4213.49 | 4210.98 |
| $SW^{UW}$ | 4463.98 | **4464.07** | 4464.94 | 4465.52 | 4465.82 | 4465.85 | 4465.59 | 4465.07 | 4464.28 | 4463.22 | 4461.90 | 4460.33 |
| $Reg^*$ | 483.27 | **4.24** | 52.14 | 100.05 | 147.95 | 195.85 | 243.76 | 291.66 | 339.56 | 387.47 | 435.37 | 483.27 |

investigated whether single-till or dual-till regulation is socially desirable in certain specific (but relevant) cases, in which social welfare equals consumers' utility, service providers' profit, or the (infrastructure) monopoly's profit. Our results demonstrated that consumers and service providers prefer single-till regulation, whilst the monopoly prefers dual-till regulation, if the profit from the non-core good is positive. The regulator's choice of single-till or dual-regulation depends on how much it values the monopoly's profit. For example, if the regulator puts more weight on the monopoly's profit, it implements dual-till regulation when there is a positive profit from the non-core good. Thus, a regulator captured by an airport tends to choose dual-till regulation.

At least two areas are worthy of investigation in future research. First, our model does not consider investment by a regulated monopoly. Czerny et al. (2016a, p. 363) state that "The consumers' position is ambiguous, and depends largely on investments." Whether dual-till regulation can be superior to single-till regulation when investment is taken into account is an important problem to be resolved. Second, we need a deeper analysis on the relationship between regulatory capture and the choice of single-till or dual-till regulation, based on real-world examples. We need more empirical research regarding the effect of personnel exchange between the regulator and the regulated monopoly on the choice of single-till or dual-till regulation. Our numerical examples are not based on actual figures. While they still add values (including illustrating the relative strengths of different individual effects and the possibility that the hybrid form of single-till and dual-till regulation yields the highest welfare), it would be important to see the results based on figures estimated from a real market. We see such empirical/numerical analyses as a natural extension of the analysis presented here, although beyond the scope of the present article.

## Author statement

Yukihiro Kidokoro: Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Writing - Review & Editing.Anming Zhang: Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Writing - Review & Editing.


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## Appendix A. Proofs of Propositions 1 and 2

First, we Prove Proposition 1. The Lagrangian for the maximization problem of (18) is formed as follows

$$\Lambda_1 = SW + \lambda_1(-Reg(p_1, p_2)) + \nu_1 \Pi^M \tag{A1}$$

where $\lambda_1 \geq 0$ and $\nu_1 \geq 0$ respectively are the Lagrangian multipliers for the regulatory constraint of $Reg(p_1, p_2) \leq 0$ and $\Pi^M \geq 0$. We assume $\lambda_1 > 0$, so that the regulatory constraint always binds, i.e., $Reg(p_1, p_2) = 0$. From (A1), applying the envelope theorem we derive

$$\frac{dSW\left(p_{1Reg1}, p_{2Reg1}\right)}{d\beta} = \frac{\partial \Lambda_1}{\partial \beta} = -\lambda_1 \Pi^{MNC}\left(p_{1Reg_1}, p_{2Reg_1}\right) \tag{A2}$$

where the subscript $Reg_1$ denotes the solution under the maximization problem of (18).

Equation (A2) implies the following relationship: i) if $\Pi^{MNC} > 0$; $\frac{dSW}{d\beta} < 0$, i.e., dual-till regulation yields higher social welfare than single-till regulation, ii) if $\Pi^{MNC} = 0$, $\frac{dSW}{d\beta} = 0$, i.e., the two types of regulations are equivalent in terms of social welfare. If $\Pi^{MNC} < 0$, $Reg(p_1, p_2) = 0$ implies $\Pi^M = 0$ when $\beta = 1$ and $\Pi^M < 0$ when $0 \leq \beta < 1$ from (20), that is, the participation constraint is satisfied only when $\beta = 1$. Thus, the only case in which the participation constraint is satisfied is single-till regulation, and accordingly, we have no relationship between $SW$ and a change in $\beta$. Proposition 1 immediately follows from these relationship.

Second, we Prove Proposition 2. The Lagrangian for the maximization problem of (19) is formed as follows

$$\Lambda_2 = SW + \lambda_2(Reg(p_1, p_2)) + \nu_2 \Pi^M \tag{A3}$$

where $\lambda_2 \geq 0$ and $\nu_2 \geq 0$ respectively are the Lagrangian multipliers for the regulatory constraint of $Reg(p_1, p_2) \geq 0$ and $\Pi^M \geq 0$. We assume $\lambda_2 > 0$, so that the regulatory constraint always binds, i.e., $Reg(p_1, p_2) = 0$. From (A3), applying the envelope theorem we derive

$$\frac{dSW\left(p_{1Reg_2}, p_{2Reg_2}\right)}{d\beta} = \frac{\partial \Lambda_2}{\partial \beta} = \lambda_2 \Pi^{MNC}\left(p_{1Reg_2}, p_{2Reg_2}\right) \tag{A4}$$

where the subscript $Reg_2$ denotes the solution under the maximization problem of (19).

Equation (A4) implies the following relationship: i) if $\Pi^{MNC} > 0$; $\frac{dSW}{d\beta} > 0$, i.e., single-till regulation yields higher social welfare than dual-till regulation, ii) if $\Pi^{MNC} = 0$, $\frac{dSW}{d\beta} = 0$, i.e., the two types of regulations are equivalent in terms of social welfare. If $\Pi^{MNC} < 0$, $Reg(p_1, p_2) = 0$ implies $\Pi^M = 0$ when $\beta = 1$ and $\Pi^M < 0$ when $0 \leq \beta < 1$ from (20), that is, the participation constraint is satisfied only when $\beta = 1$. Thus, the only case in which the participation constraint is satisfied is single-till regulation, and accordingly, we have no relationship between $SW$ and a change in $\beta$. Proposition 2 immediately follows from these relationship.

## Appendix B. Proof of Proposition 3

We prove $Reg(p_1{}^*, p_2{}^*) < 0$ to apply Proposition 2. Totally differentiating (3) and (4) and rearranging the resulting expressions, we obtain $x_1(\widetilde{p}_1, p_2)$ and $x_2(\widetilde{p}_1, p_2)$, in which

$$dx_1 = \frac{\frac{\partial^2 u}{\partial x_2{}^2} d\widetilde{p}_1 - \frac{\partial^2 u}{\partial x_1 \partial x_2} dp_2}{D}, \tag{B1}$$

$$dx_2 = \frac{-\frac{\partial^2 u}{\partial x_1 \partial x_2} d\widetilde{p}_1 + \frac{\partial^2 u}{\partial x_1{}^2} dp_2}{D} \tag{B2}$$

where

$$D \equiv \frac{\partial^2 u}{\partial x_1{}^2} \frac{\partial^2 u}{\partial x_2{}^2} - \left(\frac{\partial^2 u}{\partial x_1 \partial x_2}\right)^2 > 0 \tag{B3}$$

from (2). From (B1) and (B2), we have

$$\frac{\partial x_1}{\partial p_2} = \frac{\partial x_2}{\partial \widetilde{p}_1} = \frac{-\frac{\partial^2 u}{\partial x_1 \partial x_2}}{D}. \tag{B4}$$

When $x_1$ and $x_2$ are complementary, we have $\frac{\partial x_1}{\partial p_2} = \frac{\partial x_2}{\partial \widetilde{p}_1} < 0$, which implies

$$\frac{\partial^2 u}{\partial x_1 \partial x_2} > 0 \tag{B5}$$

from (B3). $x_1(\widetilde{p}_1, p_2)$ yields $\widetilde{p}_1(x_1, p_2)$, where

$$\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1} = \frac{D}{\frac{\partial^2 u}{\partial x_2{}^2}} < 0, \tag{B6}$$

$$\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial p_2} = \frac{\frac{\partial^2 u}{\partial x_1 \partial x_2}}{\frac{\partial^2 u}{\partial x_2{}^2}} < 0 \tag{B7}$$

from (2), (B3), and (B5).

In (7), $-\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1} \frac{x_1}{N}$ represents the mark-up per unit supply of the good that uses the core-good as input. We assume that the mark-up is fixed or smaller when the price of the non-core good, $p_2$, is higher, because higher price of the non-core good makes it difficult to charge higher price for the good that uses the core-good as input. This assumption means

$$\frac{\partial\left(-\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1} \frac{x_1}{N}\right)}{\partial p_2} \leq 0 \tag{B8}$$

which yields

$$\frac{\partial\widetilde{p}_1(x_1,p_2)}{\partial x_1 \partial p_2} \geq 0. \tag{B9}$$

Defining

$$A \equiv \left(\frac{\partial^2\widetilde{p}_1(x_1,p_2)}{\partial {x_1}^2}x_1 + \frac{\partial\widetilde{p}_1(x_1,p_2)}{\partial x_1}(1+N)\right)\frac{1}{N}\frac{\partial^2 u}{\partial {x_2}^2}, \tag{B10}$$

we also have

$$A > 0, \tag{B11}$$

$$0 < \frac{D}{A} = \frac{D}{\left(\frac{\partial^2\widetilde{p}_1(x_1,p_2)}{\partial {x_1}^2}\frac{\partial^2 u}{\partial {x_2}^2}x_1 + D\right)\frac{1}{N} + D} < 1, \tag{B12}$$

$$0 < \frac{A-D}{A} = \frac{\left(\frac{\partial^2\widetilde{p}_1(x_1,p_2)}{\partial {x_1}^2}\frac{\partial^2 u}{\partial {x_2}^2}x_1 + D\right)\frac{1}{N}}{\left(\frac{\partial^2\widetilde{p}_1(x_1,p_2)}{\partial {x_1}^2}\frac{\partial^2 u}{\partial {x_2}^2}x_1 + D\right)\frac{1}{N} + D} < 1 \tag{B13}$$

from (2), (9), (B3), (B6), and (B10).

Totally differentiating (3), (4), and (7) and rearranging the resulting expressions, we obtain

$$\begin{pmatrix} \frac{\partial^2 u}{\partial {x_1}^2} & \frac{\partial^2 u}{\partial x_1 \partial x_2} & -1 \\ \frac{\partial^2 u}{\partial x_1 \partial x_2} & \frac{\partial^2 u}{\partial {x_2}^2} & 0 \\ \left(\frac{\partial^2\widetilde{p}_1(x_1,p_2)}{\partial {x_1}^2}\frac{x_1}{N} + \frac{\partial\widetilde{p}_1(x_1,p_2)}{\partial x_1}\frac{1+N}{N}\right) & 0 & 0 \end{pmatrix}\begin{pmatrix} dx_1 \\ dx_2 \\ d\widetilde{p}_1 \end{pmatrix} = \begin{pmatrix} 0 \\ dp_2 \\ dp_1 - \left(\frac{\partial\widetilde{p}_1(x_1,p_2)}{\partial p_2} + \frac{\partial^2\widetilde{p}_1(x_1,p_2)}{\partial x_1 \partial p_2}\frac{x_1}{N}\right)dp_2 \end{pmatrix}. \tag{B14}$$

Solving (B14), we derive $\widetilde{p}_1(p_1,p_2)$ where

$$\frac{\partial\widetilde{p}_1(p_1,p_2)}{\partial p_1} = \frac{D}{A} > 0, \tag{B15}$$

$$\frac{\partial\widetilde{p}_1(p_1,p_2)}{\partial p_2} = \frac{\partial\widetilde{p}_1(x_1,p_2)}{\partial p_2}\left(\frac{A-D}{A}\right) - \frac{\partial^2\widetilde{p}_1(x_1,p_2)}{\partial x_1 \partial p_2}\frac{x_1}{N}\frac{D}{A} < 0. \tag{B16}$$

The inequality of (B15) follows from (B12). The inequality of (B16) follows from (B7), (B9), (B12), and (B13). We assume that $\frac{\partial\widetilde{p}_1(p_1,p_2)}{\partial p_2}$, i.e., the cross-price effect on the price of the good that uses the core good as input by the price of the non-core good, is small. Note that this assumption is automatically satisfied when $N$ is larger, because $\frac{A-D}{A}\to 0$ and $\frac{x_1}{N}\to 0$ as $N\to\infty$.

When $\alpha_1 = 1$ and $\alpha_2 = \alpha_3 = \alpha_4 = 0$, (16) can be written as

$$SW = U = I - \widetilde{p}_1(p_1,p_2)x_1(p_1,p_2) - p_2 x_2(p_1,p_2) + u(x_1(p_1,p_2),x_2(p_1,p_2)). \tag{B17}$$

Differentiating (B17) regarding $p_1$ and $p_2$ yields

$$\begin{aligned} \frac{\partial SW}{\partial p_1} &= -\frac{\partial\widetilde{p}_1(p_1,p_2)}{\partial p_1}x_1(p_1,p_2) \\ &-\widetilde{p}_1(p_1,p_2)\frac{\partial x_1(p_1,p_2)}{\partial p_1} - p_2\frac{\partial x_2(p_1,p_2)}{\partial p_1} \\ &+\frac{\partial u}{\partial x_1}\frac{\partial x_1(p_1,p_2)}{\partial p_1} + \frac{\partial u}{\partial x_2}\frac{\partial x_2(p_1,p_2)}{\partial p_1} \\ &= -\frac{\partial\widetilde{p}_1(p_1,p_2)}{\partial p_1}x_1(p_1,p_2), \end{aligned} \tag{B18}$$

$$\begin{aligned}\frac{\partial SW}{\partial p_2} &= -\frac{\partial \widetilde{p}_1(p_1,p_2)}{\partial p_2}x_1(p_1,p_2) \\ &-\widetilde{p}_1(p_1,p_2)\frac{\partial x_1(p_1,p_2)}{\partial p_2} \\ &-x_2(p_1,p_2)-p_2\frac{\partial x_2(p_1,p_2)}{\partial p_2} \\ &+\frac{\partial u}{\partial x_1}\frac{\partial x_1(p_1,p_2)}{\partial p_2}+\frac{\partial u}{\partial x_2}\frac{\partial x_2(p_1,p_2)}{\partial p_2} \\ &= -\frac{\partial \widetilde{p}_1(p_1,p_2)}{\partial p_2}x_1(p_1,p_2)-x_2(p_1,p_2)\end{aligned} \tag{B19}$$

from (3) and (4). Applying (B15) and the assumption that $\frac{\partial \widetilde{p}_1(p_1,p_2)}{\partial p_2}$ is small to (B18) and (B19), we have

$$\frac{\partial SW}{\partial p_1} < 0, \tag{B20}$$

$$\frac{\partial SW}{\partial p_2} < 0. \tag{B21}$$

Eqs. (B20) and (B21) lead to

$$p_1{}^* = 0, \tag{B22}$$

$$p_2{}^* = 0. \tag{B23}$$

Consequently, $Reg(p_1{}^*, p_2{}^*) < 0$. Proposition 3 immediately follows by applying Proposition 2.

## Appendix C. Proof of Proposition 4

We prove $Reg(p_1{}^*, p_2{}^*) < 0$ to apply Proposition 2. When $\alpha_2 = 1$ and $\alpha_1 = \alpha_3 = \alpha_4 = 0$, (16) is

$$SW = \Pi^S = \sum_{j=1}^{N} \pi_j^S = (\widetilde{p}_1(p_1,p_2) - p_1)x_1(p_1,p_2) \tag{C1}$$

from (5). Differentiating (C1) regarding $p_1$ and $p_2$ yields

$$\frac{\partial SW}{\partial p_1} = \left(\widetilde{p}_1(p_1,p_2) - p_1\right)\frac{\partial x_1(p_1,p_2)}{\partial p_1} + \left(\frac{\partial \widetilde{p}_1(p_1,p_2)}{\partial p_1} - 1\right)x_1(p_1,p_2), \tag{C2}$$

$$\frac{\partial SW}{\partial p_2} = \left(\widetilde{p}_1(p_1,p_2) - p_1\right)\frac{\partial x_1(p_1,p_2)}{\partial p_2} + \frac{\partial \widetilde{p}_1(p_1,p_2)}{\partial p_2}x_1(p_1,p_2). \tag{C3}$$

Solving (B14) and applying (2) and (B11), we derive $x_1(p_1,p_2)$ where

$$\frac{\partial x_1(p_1,p_2)}{\partial p_1} = \frac{\frac{\partial^2 u}{\partial x_2{}^2}}{A} < 0, \tag{C4}$$

$$\frac{\partial x_1(p_1,p_2)}{\partial p_2} = -\frac{\frac{\partial^2 u}{\partial x_1 \partial x_2}}{A} - \frac{\frac{\partial^2 \widetilde{p}_1(x_1,p_2)}{\partial x_1 \partial p_2}\frac{\partial^2 u}{\partial x_2{}^2}\frac{x_1}{N}}{A}. \tag{C5}$$

In the right hand side of (C5), the first term is negative from (B5) and (B11), while the second term, stemming from imperfect competition, is positive from (2), (B9), and (B11). We assume that the imperfect competition does not change the inequality of (C5), i.e., the second term is rather small, and consequently,

$$\frac{\partial x_1(p_1,p_2)}{\partial p_2} < 0. \tag{C6}$$

From (B13) and (B15), we derive

$$\frac{\partial \widetilde{p}_1(p_1,p_2)}{\partial p_1} - 1 = \frac{D-A}{A} < 0. \tag{C7}$$

Applying (11), (B16), (C4), (C6), and (C7) to (C2) and (C3), we have

$$\frac{\partial SW}{\partial p_1} < 0, \tag{C8}$$

$$\frac{\partial SW}{\partial p_2} < 0. \tag{C9}$$

Eqs. (C8) and (C9) lead to

$$p_1{}^* = 0, \tag{C10}$$

$$p_2{}^* = 0. \tag{C11}$$

Consequently, $Reg(p_1{}^*, p_2{}^*) < 0$. Proposition 4 immediately follows by applying Proposition 2.

## Appendix D. Corollary 1

We prove $Reg(p_1{}^*, p_2{}^*) < 0$ to apply Proposition 2. When $\alpha_1 > 0$, $\alpha_2 > 0$, and $\alpha_3 = \alpha_4 = 0$, (16) is

$$\begin{aligned} SW &= \alpha_1 U + \alpha_2 \sum_{j=1}^{N} \pi_j^S \\ &= \alpha_1 (I - \tilde{p}_1(p_1, p_2) x_1(p_1, p_2) - p_2 x_2(p_1, p_2) + u(x_1(p_1, p_2), x_2(p_1, p_2))) \\ &\quad + \alpha_2 ((\tilde{p}_1(p_1, p_2) - p_1) x_1(p_1, p_2)) \end{aligned} \tag{D1}$$

from (B17) and (C1). Differentiating (D1) regarding $p_1$ and $p_2$ yields

$$\begin{aligned} \frac{\partial SW}{\partial p_1} &= \alpha_1 \left( -\frac{\partial \tilde{p}_1(p_1, p_2)}{\partial p_1} x_1(p_1, p_2) \right) \\ &+ \alpha_2 \left( \left( \tilde{p}_1(p_1, p_2) - p_1 \right) \frac{\partial x_1(p_1, p_2)}{\partial p_1} + \left( \frac{\partial \tilde{p}_1(p_1, p_2)}{\partial p_1} - 1 \right) x_1(p_1, p_2) \right), \end{aligned} \tag{D2}$$

$$\begin{aligned} \frac{\partial SW}{\partial p_2} &= \alpha_1 \left( -\frac{\partial \tilde{p}_1(p_1, p_2)}{\partial p_2} x_1(p_1, p_2) - x_2(p_1, p_2) \right) \\ &+ \alpha_2 \left( \left( \tilde{p}_1(p_1, p_2) - p_1 \right) \frac{\partial x_1(p_1, p_2)}{\partial p_2} + \frac{\partial \tilde{p}_1(p_1, p_2)}{\partial p_2} x_1(p_1, p_2) \right). \end{aligned} \tag{D3}$$

From (B18)-(B21), (C2), (C3), (C8), and (C9), we have

$$\frac{\partial SW}{\partial p_1} < 0, \tag{D4}$$

$$\frac{\partial SW}{\partial p_2} < 0. \tag{D5}$$

Eqs. (D4) and (D5) lead to

$$p_1{}^* = 0, \tag{D6}$$

$$p_2{}^* = 0. \tag{D7}$$

Consequently, $Reg(p_1{}^*, p_2{}^*) < 0$. Corollary 1 immediately follows by applying Proposition 2.

## Appendix E. Proof of Proposition 5

Suppose that $Reg(p_1{}^*, p_2{}^*) < 0$. In this case, the regulatory constraint is

$$Reg(p_1, p_2) \geq 0 \tag{E1}$$

from (19). Using (20), (E1) can be rewritten as

$$\Pi^M \geq (1 - \beta) \Pi^{MNC}. \tag{E2}$$

When social welfare equals the profit of a monopoly, from (16) and (E2), the maximization problem is

$$\begin{aligned} &\text{Max } \alpha_3 \Pi^{MC} + \alpha_4 \Pi^{MNC}, \\ &\text{subject to } \Pi^M \geq (1 - \beta) \Pi^{MNC} \text{ and } \Pi^M \geq 0. \end{aligned} \tag{E3}$$

First, consider the case in which the maximization without constraint satisfies $\Pi^M \geq (1 - \beta) \Pi^{MNC}$. In this case, the regulation is unbinding, which case is assumed away. Second, consider the case in which the maximization without constraint satisfies $\Pi^M < (1-\beta)\Pi^{MNC}$. In this case, the maximum profit of a monopoly without constraint is $\Pi^M < (1-\beta)\Pi^{MNC}$, and consequently, it is impossible to satisfy $\Pi^M \geq (1-\beta)\Pi^{MNC}$, i.e., no solution exists. We know that the case of $Reg(p_1{}^*, p_2{}^*) < 0$ is irrelevant when social welfare equals the profit of a monopoly. Thus, we have $Reg(p_1{}^*, p_2{}^*) > 0$, and Proposition 5 immediately follows by applying Proposition 1.

## Appendix F. A model with congestion

We modify our model in Section 2 to include congestion. We consider two effects of congestion: an increase in time cost incurred by consumers and an increase in supply cost incurred by service providers. Thus, our model can correspond to either case of consumers' or service providers' congestion or both. The other parts of the model remain unchanged.

First, we formulate the congestion cost for consumers. We define the generalized price of the core good as the sum of the supply price by service providers, $\widetilde{p}_1$, and the time cost

$$\widehat{p}_1 = \widetilde{p}_1 + t_1(x_1) \tag{F1}$$

where $t_1(x_1)$ is the time cost and we assume that $\frac{dt_1}{dx_1} > 0$ and $\frac{d^2t_1}{dx_1{}^2} \geq 0$. Eq. (F1) implies that the generalized price of the core good is higher by larger time cost when the demand for the core good is larger. Utility maximization yields

$$\widehat{p}_1 = \frac{\partial u(x_1, x_2)}{\partial x_1} \tag{F2}$$

instead of (3), and (4).

Second, we model the congestion cost for service providers. The profits of service provider $j$, $\pi_j^S$, is

$$\pi_j^S = \left(\widetilde{p}_1(x_1, p_2) - p_1 - c^S(x_{1j})\right)x_{1j} \tag{F3}$$

instead of (5). In (F3), $c^S(x_{1j})$ is the cost of service provider $j$ and we assume that $\frac{dc^S}{dx_{1j}} > 0$ and $\frac{d^2c^S}{dx_{1j}{}^2} \geq 0$. Eq. (F3) implies that the cost of a service provider is higher by severer congestion when the demand for the core good is larger. Profit maximization by service provider $j$ yields

$$\frac{\partial \pi_j^S}{\partial x_{1j}} = \widetilde{p}_1(x_1, p_2) - p_1 - c^S(x_{1j}) + \left(\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1}\frac{dx_1}{dx_{1j}} - \frac{dc^S}{dx_{1j}}\right)x_{1j} = 0 \tag{F4}$$

instead of (6). From (F4), we obtain

$$\widetilde{p}_1(x_1, p_2) = p_1 + c^S\left(\frac{x_1}{N}\right) - \left(\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1} - \frac{dc^S}{d\left(\frac{x_1}{N}\right)}\right)\frac{x_1}{N} \tag{F5}$$

instead of (7). In (F5),

$$\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1} < 0 \tag{F6}$$

as we will show in (G6). Eq. (F6) and $\frac{dc^S}{dx_{1j}} > 0$ implies

$$-\left(\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1} - \frac{dc^S}{d\left(\frac{x_1}{N}\right)}\right)\frac{x_1}{N} > 0. \tag{F7}$$

We assume

$$\frac{\partial^2 \widetilde{p}_1(x_1, p_2)}{\partial x_1{}^2} < 0 \tag{F8}$$

which is sufficient for the second-order conditions being satisfied.

## Appendix G. Proof of Proposition 3 when congestion exists

The procedure of proof is the same as the proof of Proposition 3 in Appendix B, and we prove $Reg(p_1^* \ p_2^*)$ to apply Proposition 2. Totally differentiating (F2) and (4), using (F1), and rearranging the resulting expressions, we obtain $x_1(\widetilde{p}_1, p_2)$ and $x_2(\widetilde{p}_1, p_2)$, in which

$$dx_1 = \frac{\frac{\partial^2 u}{\partial x_2{}^2}d\widetilde{p}_1 - \frac{\partial^2 u}{\partial x_1 \partial x_2}dp_2}{D^{`}}, \tag{G1}$$

$$dx_2 = \frac{-\frac{\partial^2 u}{\partial x_1 \partial x_2} d\widetilde{p}_1 + \left(\frac{\partial^2 u}{\partial x_1^2} - \frac{dt}{dx_1}\right) dp_2}{D'} \tag{G2}$$

where

$$D' \equiv \left(\frac{\partial^2 u}{\partial x_1^2} - \frac{dt}{dx_1}\right) \frac{\partial^2 u}{\partial x_2^2} - \left(\frac{\partial^2 u}{\partial x_1 \partial x_2}\right)^2 > 0 \tag{G3}$$

from (2) and $\frac{dt_1}{dx_1} > 0$. From (G1) and (G2), we have

$$\frac{\partial x_1}{\partial p_2} = \frac{\partial x_2}{\partial \widetilde{p}_1} = \frac{-\frac{\partial^2 u}{\partial x_1 \partial x_2}}{D'}. \tag{G4}$$

When $x_1$ and $x_2$ are complementary, we have $\frac{\partial x_1}{\partial p_2} = \frac{\partial x_2}{\partial \widetilde{p}_1} < 0$, which implies

$$\frac{\partial^2 u}{\partial x_1 \partial x_2} > 0 \tag{G5}$$

from (G3). $x_1(\widetilde{p}_1, p_2)$ yields $\widetilde{p}_1(x_1, p_2)$, where

$$\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1} = \frac{D'}{\frac{\partial^2 u}{\partial x_2^2}} < 0, \tag{G6}$$

$$\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial p_2} = \frac{\frac{\partial^2 u}{\partial x_1 \partial x_2}}{\frac{\partial^2 u}{\partial x_2^2}} < 0 \tag{G7}$$

from (2), (G3), and (G5).

In (F5), $-\left(\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1} - \frac{dc^S}{d\left(\frac{x_1}{N}\right)}\right) \frac{x_1}{N}$ represents the mark-up per unit supply of the good that uses the core-good as input. We assume that the mark-up is fixed or smaller when the price of the non-core good, $p_2$, is higher, because higher price of the non-core good makes it difficult to charge higher price for the good that uses the core-good as input. This assumption means

$$\frac{\partial\left(-\left(\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1} - \frac{dc^S}{d\left(\frac{x_1}{N}\right)}\right) \frac{x_1}{N}\right)}{\partial p_2} \le 0 \tag{G8}$$

which yields

$$\frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1 \partial p_2} \ge 0. \tag{G9}$$

Defining

$$A' \equiv \left(\frac{\partial^2 \widetilde{p}_1(x_1, p_2)}{\partial x_1^2} \frac{x_1}{N} + \frac{\partial \widetilde{p}_1(x_1, p_2)}{\partial x_1} \frac{1+N}{N} - \frac{d^2 c^S}{d\left(\frac{x_1}{N}\right)^2} \frac{x_1}{N^2} - 2\frac{dc^S}{d\left(\frac{x_1}{N}\right)} \frac{1}{N}\right) \frac{\partial^2 u}{\partial x_2^2}, \tag{G10}$$

we have

$$A' > 0, \tag{G11}$$

$$0 < \frac{D'}{A'} = \frac{D'}{\left(\left(\frac{\partial^2 \widetilde{p}_1(x_1, p_2)}{\partial x_1^2} x_1 - \frac{d^2 c^S}{d\left(\frac{x_1}{N}\right)^2} \frac{x_1}{N} - 2\frac{dc^S}{d\left(\frac{x_1}{N}\right)}\right) \frac{\partial^2 u}{\partial x_2^2} + D'\right) \frac{1}{N} + D'} < 1, \tag{G12}$$

$$0 < \frac{D}{A'} = \frac{D' + \frac{dt}{dx_1} \frac{\partial^2 u}{\partial x_2^2}}{\left(\left(\frac{\partial^2 \widetilde{p}_1(x_1, p_2)}{\partial x_1^2} x_1 - \frac{d^2 c^S}{d\left(\frac{x_1}{N}\right)^2} \frac{x_1}{N} - 2\frac{dc^S}{d\left(\frac{x_1}{N}\right)}\right) \frac{\partial^2 u}{\partial x_2^2} + D'\right) \frac{1}{N} + D'} < 1, \tag{G13}$$

$$0 < \frac{A' - D'}{A'} = \frac{\left(\left(\frac{\partial^2 \widetilde{p}_1(x_1, p_2)}{\partial x_1^2} x_1 - \frac{d^2 c^S}{d\left(\frac{x_1}{N}\right)^2} \frac{x_1}{N} - 2\frac{dc^S}{d\left(\frac{x_1}{N}\right)}\right) \frac{\partial^2 u}{\partial x_2^2} + D'\right) \frac{1}{N}}{\left(\left(\frac{\partial^2 \widetilde{p}_1(x_1, p_2)}{\partial x_1^2} x_1 - \frac{d^2 c^S}{d\left(\frac{x_1}{N}\right)^2} \frac{x_1}{N} - 2\frac{dc^S}{d\left(\frac{x_1}{N}\right)}\right) \frac{\partial^2 u}{\partial x_2^2} + D'\right) \frac{1}{N} + D'} < 1, \tag{G14}$$

$$0<\frac{A'-D}{A'}=\frac{\left(\left(\frac{\partial^2\widetilde{p}_1(x_1,p_2)}{\partial x_1{}^2}x_1-\frac{d^2c^S}{d\left(\frac{x_1}{N}\right)^2}\frac{x_1}{N}-2\frac{dc^S}{d\left(\frac{x_1}{N}\right)}\right)\frac{\partial^2u}{\partial x_2{}^2}+D'\right)\frac{1}{N}-\frac{dt}{dx_1}\frac{\partial^2u}{\partial x_2{}^2}}{\left(\left(\frac{\partial^2\widetilde{p}_1(x_1,p_2)}{\partial x_1{}^2}x_1-\frac{d^2c^S}{d\left(\frac{x_1}{N}\right)^2}\frac{x_1}{N}-2\frac{dc^S}{d\left(\frac{x_1}{N}\right)}\right)\frac{\partial^2u}{\partial x_2{}^2}+D'\right)\frac{1}{N}+D'}<1 \tag{G15}$$

from (2), (B3), (F8), (G3), (G6), $\frac{dt_1}{dx_1}$, $\frac{dc^s}{dx_{1j}}$ and $\frac{d^2c^s}{dx_{1j}{}^2}\geq 0$.

Totally differentiating (4), (F2), and (F5) and rearranging the resulting expressions, we obtain

$$\begin{pmatrix} \frac{\partial^2u(x_1,x_2)}{\partial x_1{}^2}-\frac{dt}{dx_1} & \frac{\partial^2u(x_1,x_2)}{\partial x_1\partial x_2} & -1 \\ \frac{\partial^2u(x_1,x_2)}{\partial x_1\partial x_2} & \frac{\partial^2u(x_1,x_2)}{\partial x_2{}^2} & 0 \\ \frac{\partial^2\widetilde{p}_1(x_1,p_2)}{\partial x_1{}^2}\frac{x_1}{N}+\frac{\partial\widetilde{p}_1(x_1,p_2)}{\partial x_1}\frac{1+N}{N}-\frac{d^2c^S}{d\left(\frac{x_1}{N}\right)^2}\frac{x_1}{N^2}-2\frac{dc^S}{d\left(\frac{x_1}{N}\right)}\frac{1}{N} & 0 & 0 \end{pmatrix}\begin{pmatrix} dx_1 \\ dx_2 \\ d\widetilde{p}_1 \end{pmatrix} = \begin{pmatrix} 0 \\ dp_2 \\ dp_1-\left(\frac{\partial\widetilde{p}_1(x_1,p_2)}{\partial p_2}+\frac{\partial^2\widetilde{p}_1(x_1,p_2)}{\partial x_1\partial p_2}\frac{x_1}{N}\right)dp_2 \end{pmatrix}. \tag{G16}$$

Solving (G16) and applying (2), (G7), (G9), (G11), (G12), and (G14), we derive $\partial\widetilde{p}_1(p_1,p_2)$ and $x_1(p_1,p_2)$, where

$$\frac{\partial\widetilde{p}_1(p_1,p_2)}{\partial p_1}=\frac{D^{'}}{A^{'}}>0, \tag{G17}$$

$$\frac{\partial\widetilde{p}_1(p_1,p_2)}{\partial p_2}=\frac{\partial\widetilde{p}_1(x_1,p_2)}{\partial p_2}\left(\frac{A^{'}-D^{'}}{A^{'}}\right)-\frac{\partial^2\widetilde{p}_1(x_1,p_2)}{\partial x_1\partial p_2}\frac{x_1}{N}\frac{D^{'}}{A^{'}}<0, \tag{G18}$$

$$\frac{\partial x_1(p_1,p_2)}{\partial p_1}=\frac{\frac{\partial^2u}{\partial x_2{}^2}}{A^{'}}<0, \tag{G19}$$

$$\frac{\partial x_1(p_1,p_2)}{\partial p_2}=-\frac{\frac{\partial^2u}{\partial x_1\partial x_2}}{A^{'}}-\frac{\frac{\partial^2\widetilde{p}_1(x_1,p_2)}{\partial x_1\partial p_2}\frac{\partial^2u}{\partial x_2{}^2}\frac{x_1}{N}}{A^{'}}. \tag{G20}$$

In the right hand side of (G20), the first term is negative from (G5) and (G11), while the second term, stemming from imperfect competition, is positive from (2), (G9), and (G11). We assume that the imperfect competition does not change the inequality of (G20), i.e., the second term is rather small in the same way as (C5) in Appendix C, and consequently,

$$\frac{\partial x_1(p_1,p_2)}{\partial p_2}<0. \tag{G21}$$

From (B3), (F1), (G3), (G7), (G9), (G13), (G15), and (G17)-(G20), we have

$$\begin{aligned}\frac{\partial\widehat{p}_1(p_1,p_2)}{\partial p_1} &=\frac{\partial\left(\widetilde{p}_1(p_1,p_2)+t(x_1)\right)}{\partial p_1} \\ &=\frac{\partial\widetilde{p}_1(p_1,p_2)}{\partial p_1}+\frac{dt}{dx_1}\frac{\partial x_1(p_1,p_2)}{\partial p_1} \\ &=\frac{D^{'}}{A^{'}}+\frac{dt}{dx_1}\frac{\frac{\partial^2u}{\partial x_2{}^2}}{A^{'}} \\ &=\frac{D}{A^{'}}>0,\end{aligned} \tag{G22}$$

$$\frac{\partial\widehat{p}_1(p_1,p_2)}{\partial p_2} = \frac{\partial\left(\widetilde{p}_1(p_1,p_2)+t(x_1)\right)}{\partial p_2} = \frac{\partial\widetilde{p}_1(p_1,p_2)}{\partial p_2}+\frac{dt}{dx_1}\frac{\partial x_1(p_1,p_2)}{\partial p_2} = \frac{\partial\widetilde{p}_1(x_1,p_2)}{\partial p_2}\left(\frac{A^{`}-D}{A^{`}}\right)-\frac{\partial^2\widetilde{p}_1(x_1,p_2)}{\partial x_1\partial p_2}\frac{x_1}{N}\frac{D}{A^{`}}<0. \tag{G23}$$

In (G23), we again assume that $\frac{\partial\widehat{p}_1(p_1,p_2)}{\partial p_2}$, i.e., the cross-price effect on the price of the good that uses the core good as input by the price of the non-core good, is small in the same way as (B16) in Appendix B.

When congestion exists (B17), is

$$SW=U=I-\widehat{p}_1(p_1,p_2)x_1(p_1,p_2)-p_2x_2(p_1,p_2)+u(x_1(p_1,p_2),x_2(p_1,p_2)). \tag{G24}$$

Differentiating (G24) regarding $p_1$ and $p_2$ yields

$$\frac{\partial SW}{\partial p_1}=\frac{\partial\widehat{p}_1(p_1,p_2)}{\partial p_1}x_1(p_1,p_2) -\widehat{p}_1(p_1,p_2)\frac{\partial x_1(p_1,p_2)}{\partial p_1}-p_2\frac{\partial x_2(p_1,p_2)}{\partial p_1} +\frac{\partial u}{\partial x_1}\frac{\partial x_1(p_1,p_2)}{\partial p_1}+\frac{\partial u}{\partial x_2}\frac{\partial x_2(p_1,p_2)}{\partial p_1} =-\frac{\partial\widehat{p}_1(p_1,p_2)}{\partial p_1}x_1(p_1,p_2), \tag{G25}$$

$$\frac{\partial SW}{\partial p_2}=\frac{\partial\widehat{p}_1(p_1,p_2)}{\partial p_2}x_1(p_1,p_2) -\widehat{p}_1(p_1,p_2)\frac{\partial x_1(p_1,p_2)}{\partial p_2} -x_2(p_1,p_2)-p_2\frac{\partial x_2(p_1,p_2)}{\partial p_1} +\frac{\partial u}{\partial x_1}\frac{\partial x_1(p_1,p_2)}{\partial p_2}+\frac{\partial u}{\partial x_2}\frac{\partial x_2(p_1,p_2)}{\partial p_1} =-\frac{\partial\widehat{p}_1(p_1,p_2)}{\partial p_2}x_1(p_1,p_2)-x_2(p_1,p_2) \tag{G26}$$

from (F2) and (4). Applying (G22) and the assumption that $\frac{\partial\widehat{p}_1(p_1,p_2)}{\partial p_2}$ is small to (G25) and (G26), we have (B20) and (B21), which lead to (B22) and (B23). Consequently, $Reg({p_1}^*,{p_2}^*)<0$. We then derive the same result as Appendix B.

## Appendix H. Proof of Proposition 4 when congestion exists

We prove $Reg({p_1}^*,{p_2}^*)<0$ to apply Proposition 2. When congestion exists (C1), is

$$SW=\Pi^S=\sum_{j=1}^{N}\pi_j^S=\left(\widetilde{p}_1(p_1,p_2)-p_1-c^S\left(\frac{x_1(p_1,p_2)}{N}\right)\right)x_1(p_1,p_2) \tag{H1}$$

from (F3). Differentiating (H1) regarding $p_1$ and $p_2$ yields

$$\frac{\partial SW}{\partial p_1}=\left(\widetilde{p}_1(p_1,p_2)-p_1-c^S\left(\frac{x_1(p_1,p_2)}{N}\right)\right)\frac{\partial x_1(p_1,p_2)}{\partial p_1} +\left(\frac{\partial\widetilde{p}_1(p_1,p_2)}{\partial p_1}-1-\frac{dc^S}{d\left(\frac{x_1}{N}\right)}\frac{1}{N}\frac{\partial x_1(p_1,p_2)}{\partial p_1}\right)x_1(p_1,p_2), \tag{H2}$$

$$\frac{\partial SW}{\partial p_2}=\left(\widetilde{p}_1(p_1,p_2)-p_1-c^S\left(\frac{x_1(p_1,p_2)}{N}\right)\right)\frac{\partial x_1(p_1,p_2)}{\partial p_2} +\left(\frac{\partial\widetilde{p}_1(p_1,p_2)}{\partial p_2}-\frac{dc^S}{d\left(\frac{x_1}{N}\right)}\frac{1}{N}\frac{\partial x_1(p_1,p_2)}{\partial p_2}\right)x_1(p_1,p_2). \tag{H3}$$

From (2), (F8), (G3), (G5), (G9)-(G11), (G17)-(G20), $\frac{dc^S}{dx_{1j}}>0$ and $\frac{d^2c^S}{d{x_{1j}}^2}\geq 0$, we derive

$$\frac{\partial \tilde{p}_1(p_1,p_2)}{\partial p_1} - 1 - \frac{dc^S}{d\left(\frac{x_1}{N}\right)}\frac{1}{N}\frac{\partial x_1(p_1,p_2)}{\partial p_1} = \frac{-\left(\left(\frac{\partial^2 \tilde{p}_1(x_1,p_2)}{\partial {x_1}^2}x_1 - \frac{d^2c^S}{d\left(\frac{x_1}{N}\right)^2}\frac{x_1}{N} - \frac{dc^S}{d\left(\frac{x_1}{N}\right)}\right)\frac{\partial^2 u}{\partial {x_2}^2} + D^{'}\right)\frac{1}{N}}{A^{'}} < 0, \tag{H4}$$

$$\frac{\partial \tilde{p}_1(p_1,p_2)}{\partial p_2} - \frac{dc^S}{d\left(\frac{x_1}{N}\right)}\frac{1}{N}\frac{\partial x_1(p_1,p_2)}{\partial p_2} = \frac{\frac{\partial^2 u}{\partial x_1 \partial x_2}\left(\frac{\partial^2 \tilde{p}_1(x_1,p_2)}{\partial {x_1}^2}x_1 - \frac{d^2c^S}{d\left(\frac{x_1}{N}\right)^2}\frac{x_1}{N} - \frac{dc^S}{d\left(\frac{x_1}{N}\right)} + \frac{D^{'}}{\frac{\partial^2 u}{\partial {x_2}^2}}\right)\frac{1}{N} - \frac{\partial^2 \tilde{p}_1(x_1,p_2)}{\partial x_1 \partial p_2}\left(x_1 D^{'} - \frac{dc^S}{d\left(\frac{x_1}{N}\right)}\left(\frac{\partial^2 u}{\partial {x_2}^2}\frac{x_1}{N}\right)\right)\frac{1}{N}}{A^{'}} < 0. \tag{H5}$$

Applying (F5), (F7), (G19), (G20), (H4), (H5), and $\frac{dc^S}{dx_{1j}} > 0$ to (H2) and (H3), we have (C8) and (C9), which lead to (C10) and (C11). Consequently, $Reg({p_1}^*,{p_2}^*) < 0$. Proposition 4 immediately follows by applying Proposition 2.

### Appendix I. Proof of Corollary 1 when congestion exists

We prove $Reg({p_1}^*,{p_2}^*) < 0$ to apply Proposition 2, using the results in Appendixes G and H. The procedure is totally the same as Appendix D, and omitted.

### Appendix J. Proof of Proposition 5 when congestion exists

Congestion has no effect on the proof of Proposition 5 shown in Appendix E. Thus, Proposition 5 holds without modification even if congestion exists.

### Appendix K. Numerical examples when congestion exists

We set $t_1(x_1) = 10x_1$ and $c^S(x_{1j}) = 10x_{1j}$ in (F1) and (F3). The results are shown in Tables A-1 to A-7. Tables A-1 to A-3 illustrates the same results as Tables 1–3, as implied by Propositions 3 to 5, although the cases in which participation constraint is satisfied are different. In Tables A-4 to A-6, dual-till regulation is superior to single-till regulation, while in Tables 4 and 6, single-till regulation is superior and in Table 5, the hybrid of single-till and dual-till regulation is superior. This is because congestion makes consumers utility lower and consequently, the relative importance of monopoly's profit in social welfare is larger. Thus, when social welfare equals the sum of consumer's utility, service providers' profits, and a monopoly's profit, the effect by Proposition 5 dominates the effects by Propositions 3 and 4. In Table A-7, dual-till regulation is superior to single-till regulation, which is the same result as Table 7.

**Table A-1**
When social welfare equals consumer's utility in the case of congestion

| | Case 1 | Case 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0 | *0* | *0.1* | *0.2* | *0.3* | *0.4* | *0.5* | *0.6* | *0.7* | *0.8* | *0.9* | **1** |
| $p_1$ | 0.00 | *23.34* | *59.90* | *60.74* | *61.81* | *63.01* | *64.30* | *65.68* | *67.15* | *68.73* | *70.40* | **72.17** |
| $\tilde{p}_1$ | 54.59 | *69.43* | *76.40* | *76.71* | *77.32* | *78.04* | *78.84* | *79.71* | *80.64* | *81.64* | *82.70* | **83.83** |
| $p_2$ | 0.00 | *0.00* | *89.52* | *90.72* | *91.14* | *91.34* | *91.45* | *91.52* | *91.56* | *91.58* | *91.59* | **91.60** |
| $mc_1$ | 30.00 | *30.00* | *30.00* | *30.00* | *30.00* | *30.00* | *30.00* | *30.00* | *30.00* | *30.00* | *30.00* | **30.00** |
| $mc_2$ | 2088.76 | *2074.94* | *236.36* | *211.52* | *202.47* | *197.66* | *194.60* | *192.41* | *190.72* | *189.32* | *188.11* | **187.01** |
| $x_1$ | 8.88 | *7.49* | *2.68* | *2.60* | *2.52* | *2.45* | *2.37* | *2.28* | *2.19* | *2.10* | *2.00* | **1.90** |
| $x_2$ | 104.44 | *103.75* | *11.82* | *10.58* | *10.12* | *9.88* | *9.73* | *9.62* | *9.54* | *9.47* | *9.41* | **9.35** |
| $U$ | 5039.54 | *5031.06* | *67.58* | *55.56* | *51.66* | *49.74* | *48.62* | *47.90* | *47.41* | *47.07* | *46.82* | **46.65** |
| $\Pi^S$ | 326.93 | *233.09* | *29.87* | *28.01* | *26.39* | *24.81* | *23.22* | *21.61* | *19.96* | *18.29* | *16.60* | **14.91** |
| $\Pi^{MC}$ | −188.76 | *0.00* | *33.87* | *31.80* | *30.66* | *29.61* | *28.44* | *27.04* | *25.35* | *23.30* | *20.81* | **17.83** |
| $\Pi^{MNC}$ | −109073 | *−107635* | *−338.70* | *−159.00* | *−102.21* | *−74.03* | *−56.88* | *−45.07* | *−36.22* | *−29.12* | *−23.12* | **−17.83** |
| $\Pi^M$ | −109261 | *−107635* | *−304.83* | *−127.20* | *−71.54* | *−44.42* | *−28.44* | *−18.03* | *−10.87* | *−5.82* | *−2.31* | **0.00** |
| $SW$ | 5039.54 | *5031.06* | *67.58* | *55.56* | *51.66* | *49.74* | *48.62* | *47.90* | *47.41* | *47.07* | *46.82* | **46.65** |
| $SW^{UW}$ | −103895 | *−102371* | *−207.38* | *−43.64* | *6.50* | *30.14* | *43.41* | *51.48* | *56.51* | *59.54* | *61.12* | **61.56** |
| $Reg^*$ | −109261 | *−189* | *−11096* | *−22003* | *−32911* | *−43818* | *−54725* | *−65632* | *−76540* | *−87447* | *−98354* | **−109261** |

**Table A-2**
When social welfare equals service providers' profit in the case of congestion

| | Case 1 | Case 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0 | *0* | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | **1** |
| $p_1$ | 0.00 | *23.34* | 27.65 | 21.16 | 15.69 | 10.86 | 6.47 | 2.44 | 0.00 | 0.00 | 0.00 | **0.00** |
| $\widetilde{p}_1$ | 54.59 | *69.43* | 54.61 | 50.36 | 46.83 | 43.71 | 40.90 | 38.30 | 36.89 | 37.05 | 37.13 | **37.19** |
| $p_2$ | 0.00 | *0.00* | 96.55 | 97.18 | 97.49 | 97.70 | 97.87 | 98.02 | 97.25 | 96.40 | 95.94 | **95.63** |
| $mc_1$ | 30.00 | *30.00* | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | **30.00** |
| $mc_2$ | 2088.76 | *2074.94* | 112.83 | 103.86 | 100.88 | 99.41 | 98.54 | 97.98 | 115.01 | 132.20 | 141.52 | **147.85** |
| $x_1$ | 8.88 | *7.49* | 4.38 | 4.75 | 5.06 | 5.34 | 5.60 | 5.83 | 6.00 | 6.02 | 6.04 | **6.05** |
| $x_2$ | 104.44 | *103.75* | 5.64 | 5.19 | 5.04 | 4.97 | 4.93 | 4.90 | 5.75 | 6.61 | 7.08 | **7.39** |
| $U$ | 5039.54 | *5031.06* | 23.15 | 22.43 | 22.77 | 23.35 | 24.01 | 24.72 | 27.28 | 30.08 | 31.90 | **33.25** |
| $\Pi^S$ | 326.93 | *233.09* | 79.73 | 93.57 | 106.39 | 118.46 | 130.00 | 141.14 | 149.33 | 150.58 | 151.26 | **151.72** |
| $\Pi^{MC}$ | −188.76 | *0.00* | −22.64 | −47.00 | −71.19 | −95.43 | −119.73 | −144.11 | −159.99 | −160.24 | −160.37 | **−160.46** |
| $\Pi^{MNC}$ | −109073 | *−107635* | 226.43 | 234.99 | 237.31 | 238.56 | 239.46 | 240.18 | 228.55 | 200.30 | 178.19 | **160.46** |
| $\Pi^M$ | −109261 | *−107635* | 203.78 | 187.99 | 166.11 | 143.14 | 119.73 | 96.07 | 68.57 | 40.06 | 17.82 | **0.00** |
| $SW$ | 326.93 | *233.09* | 79.73 | 93.57 | 106.39 | 118.46 | 130.00 | 141.14 | 149.33 | 150.58 | 151.26 | **151.72** |
| $SW^{UW}$ | −103895 | *−102371* | 306.67 | 303.99 | 295.27 | 284.95 | 273.75 | 261.93 | 245.17 | 220.72 | 200.98 | **184.98** |
| $Reg^*$ | −109261 | *−189* | −11096 | −22003 | −32911 | −43818 | −54725 | −65632 | −76540 | −87447 | −98354 | **−109261** |

**Table A-3**
When social welfare equals a monopoly's profit in the case of congestion

| | Case 1 | Case 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0.00 | **0.00** | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 | 0.60 | 0.70 | 0.80 | 0.90 | 1.00 |
| $p_1$ | 55.00 | **35.77** | 27.48 | 21.05 | 15.60 | 10.78 | 6.41 | 2.38 | 0.00 | 0.00 | 0.00 | 9.41 |
| $\widetilde{p}_1$ | 71.97 | **59.64** | 54.32 | 50.20 | 46.70 | 43.61 | 40.81 | 38.22 | 36.50 | 36.35 | 36.27 | 43.36 |
| $p_2$ | 96.71 | **97.30** | 97.53 | 97.71 | 97.86 | 98.00 | 98.12 | 98.23 | 99.39 | 100.23 | 100.69 | 94.56 |
| $mc_1$ | 30.00 | **30.00** | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| $mc_2$ | 93.42 | **92.77** | 92.97 | 93.13 | 93.27 | 93.40 | 93.51 | 93.62 | 71.60 | 54.50 | 45.26 | 163.93 |
| $x_1$ | 2.76 | **3.88** | 4.36 | 4.74 | 5.06 | 5.34 | 5.59 | 5.83 | 5.94 | 5.91 | 5.90 | 5.52 |
| $x_2$ | 4.67 | **4.64** | 4.65 | 4.66 | 4.66 | 4.67 | 4.68 | 4.68 | 3.58 | 2.73 | 2.26 | 8.20 |
| $U$ | 18.27 | **19.29** | 20.18 | 21.04 | 21.87 | 22.69 | 23.50 | 24.30 | 23.40 | 23.13 | 23.27 | 36.21 |
| $\Pi^S$ | 31.61 | **62.49** | 79.05 | 93.21 | 106.14 | 118.27 | 129.84 | 140.99 | 146.19 | 144.97 | 144.31 | 126.52 |
| $\Pi^{MC}$ | 24.20 | **0.00** | −23.73 | −47.63 | −71.67 | −95.83 | −120.08 | −144.43 | −159.35 | −159.10 | −158.97 | −103.28 |
| $\Pi^{MNC}$ | 233.55 | **236.18** | 237.30 | 238.17 | 238.91 | 239.57 | 240.16 | 240.71 | 227.65 | 198.88 | 176.63 | 103.28 |
| $\Pi^M$ | 257.75 | **236.18** | 213.57 | 190.54 | 167.24 | 143.74 | 120.08 | 96.29 | 68.29 | 39.78 | 17.66 | 0.00 |
| $SW$ | 257.75 | **236.18** | 213.57 | 190.54 | 167.24 | 143.74 | 120.08 | 96.29 | 68.29 | 39.78 | 17.66 | 0.00 |
| $SW^{UW}$ | 307.64 | **317.95** | 312.80 | 304.79 | 295.24 | 284.70 | 273.42 | 261.58 | 237.89 | 207.87 | 185.25 | 162.72 |
| $Reg^*$ | 257.75 | **24.20** | 47.56 | 70.91 | 94.27 | 117.62 | 140.98 | 164.33 | 187.69 | 211.04 | 234.39 | 257.75 |

**Table A-4**
When social welfare equals the unweighted sum of consumer's utility, service providers' profits, and a monopoly's profit in the case of congestion

| | Case 1 | Case 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0 | **0** | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
| $p_1$ | 39.02 | **35.71** | 27.46 | 21.05 | 15.62 | 10.81 | 6.46 | 2.44 | 0.00 | 0.00 | 0.00 | 0.00 |
| $\widetilde{p}_1$ | 61.76 | **59.63** | 54.34 | 50.23 | 46.75 | 43.67 | 40.88 | 38.30 | 36.89 | 37.05 | 37.13 | 37.19 |
| $p_2$ | 97.00 | **97.10** | 97.34 | 97.52 | 97.67 | 97.80 | 97.91 | 98.01 | 97.25 | 96.40 | 95.94 | 95.63 |
| $mc_1$ | 30.00 | **30.00** | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| $mc_2$ | 97.00 | **96.87** | 96.83 | 96.96 | 97.15 | 97.40 | 97.69 | 98.03 | 115.01 | 132.20 | 141.52 | 147.85 |
| $x_1$ | 3.70 | **3.89** | 4.37 | 4.74 | 5.06 | 5.34 | 5.60 | 5.83 | 6.00 | 6.02 | 6.04 | 6.05 |
| $x_2$ | 4.85 | **4.84** | 4.84 | 4.85 | 4.86 | 4.87 | 4.88 | 4.90 | 5.75 | 6.61 | 7.08 | 7.39 |
| $U$ | 19.63 | **19.88** | 20.69 | 21.51 | 22.31 | 23.12 | 23.92 | 24.72 | 27.28 | 30.08 | 31.90 | 33.25 |
| $\Pi^S$ | 56.72 | **62.80** | 79.29 | 93.42 | 106.33 | 118.44 | 130.00 | 141.14 | 149.33 | 150.58 | 151.26 | 151.72 |
| $\Pi^{MC}$ | 7.29 | **0.00** | −23.69 | −47.55 | −71.55 | −95.65 | −119.84 | −144.10 | −159.99 | −160.24 | −160.37 | −160.46 |
| $\Pi^{MNC}$ | 235.22 | **235.72** | 236.89 | 237.77 | 238.49 | 239.12 | 239.68 | 240.17 | 228.55 | 200.30 | 178.19 | 160.46 |
| $\Pi^M$ | 242.51 | **235.72** | 213.20 | 190.21 | 166.95 | 143.47 | 119.84 | 96.07 | 68.57 | 40.06 | 17.82 | 0.00 |
| $SW$ | 318.86 | **318.39** | 313.18 | 305.14 | 295.59 | 285.04 | 273.76 | 261.93 | 245.17 | 220.72 | 200.98 | 184.98 |
| $SW^{UW}$ | 318.86 | **318.39** | 313.18 | 305.14 | 295.59 | 285.04 | 273.76 | 261.93 | 245.17 | 220.72 | 200.98 | 184.98 |
| $Reg^*$ | 242.51 | **7.29** | 30.81 | 54.34 | 77.86 | 101.38 | 124.90 | 148.42 | 171.94 | 195.47 | 218.99 | 242.51 |

**Table A-5**
When social welfare equals the unweighted sum of consumer's utility, service providers' profits, and a monopoly's profit in the case of congestion and $N = 100$

| | Case 1 | Case 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0 | **0** | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
| $p_1$ | 53.13 | **24.52** | 20.43 | 16.74 | 13.35 | 10.19 | 7.22 | 4.42 | 1.75 | 0.00 | 0.00 | 0.00 |
| $\tilde{p}_1$ | 54.47 | **26.64** | 22.66 | 19.07 | 15.77 | 12.70 | 9.81 | 7.08 | 4.48 | 2.80 | 2.81 | 2.82 |
| $p_2$ | 97.31 | **98.66** | 98.83 | 98.99 | 99.13 | 99.26 | 99.38 | 99.50 | 99.60 | 98.86 | 98.01 | 97.55 |
| $mc_1$ | 30.00 | **30.00** | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| $mc_2$ | 97.31 | **95.74** | 95.87 | 96.01 | 96.16 | 96.32 | 96.51 | 96.74 | 97.05 | 113.85 | 131.20 | 140.60 |
| $x_1$ | 4.36 | **6.89** | 7.25 | 7.58 | 7.88 | 8.16 | 8.42 | 8.67 | 8.90 | 9.10 | 9.13 | 9.15 |
| $x_2$ | 4.87 | **4.79** | 4.79 | 4.80 | 4.81 | 4.82 | 4.83 | 4.84 | 4.85 | 5.69 | 6.56 | 7.03 |
| $U$ | 20.74 | **28.69** | 30.39 | 32.03 | 33.64 | 35.21 | 36.76 | 38.29 | 39.81 | 41.68 | 43.27 | 44.44 |
| $\Pi^S$ | 3.94 | **9.84** | 10.90 | 11.91 | 12.87 | 13.80 | 14.70 | 15.59 | 16.45 | 17.17 | 17.31 | 17.39 |
| $\Pi^{MC}$ | 88.06 | **0.00** | −24.40 | −48.95 | −73.63 | −98.44 | −123.36 | −148.38 | −173.49 | −190.95 | −191.34 | −191.55 |
| $\Pi^{MNC}$ | 236.75 | **243.11** | 243.97 | 244.74 | 245.45 | 246.11 | 246.72 | 247.30 | 247.84 | 238.69 | 212.60 | 191.55 |
| $\Pi^M$ | 324.81 | **243.11** | 219.57 | 195.79 | 171.81 | 147.66 | 123.36 | 98.92 | 74.35 | 47.74 | 21.26 | 0.00 |
| $SW$ | 349.49 | **281.64** | 260.86 | 239.73 | 218.32 | 196.68 | 174.83 | 152.80 | 130.61 | 106.58 | 81.84 | 61.82 |
| $SW^{UW}$ | 349.49 | **281.64** | 260.86 | 239.73 | 218.32 | 196.68 | 174.83 | 152.80 | 130.61 | 106.58 | 81.84 | 61.82 |
| $Reg^*$ | 324.81 | **88.06** | 111.73 | 135.41 | 159.08 | 182.76 | 206.43 | 230.11 | 253.78 | 277.46 | 301.13 | 324.81 |

**Table A-6**
When social welfare equals the unweighted sum of consumer's utility, service providers' profits, and a monopoly's profit with the weight for the non-core profit of 0.5 in the case of congestion

| | Case 1 | Case 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0 | **0** | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
| $p_1$ | 39.93 | **35.64** | 27.47 | 21.12 | 15.76 | 11.06 | 6.92 | 3.45 | 1.78 | 7.55 | 16.90 | 22.88 |
| $\tilde{p}_1$ | 62.39 | **59.63** | 54.39 | 50.32 | 46.89 | 43.90 | 41.27 | 39.09 | 38.13 | 42.08 | 48.23 | 52.13 |
| $p_2$ | 96.73 | **96.88** | 97.12 | 97.27 | 97.37 | 97.42 | 97.40 | 97.23 | 96.66 | 95.15 | 93.99 | 93.47 |
| $mc_1$ | 30.00 | **30.00** | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 | 30.00 |
| $mc_2$ | 101.83 | **101.36** | 101.39 | 102.06 | 103.21 | 104.98 | 107.89 | 113.30 | 125.87 | 153.16 | 171.14 | 178.24 |
| $x_1$ | 3.65 | **3.90** | 4.38 | 4.75 | 5.06 | 5.34 | 5.58 | 5.79 | 5.91 | 5.61 | 5.09 | 4.76 |
| $x_2$ | 5.09 | **5.07** | 5.07 | 5.10 | 5.16 | 5.25 | 5.39 | 5.67 | 6.29 | 7.66 | 8.56 | 8.91 |
| $U$ | 20.33 | **20.57** | 21.33 | 22.18 | 23.07 | 24.02 | 25.08 | 26.42 | 28.67 | 33.59 | 37.79 | 39.83 |
| $\Pi^S$ | 55.32 | **63.15** | 79.50 | 93.56 | 106.36 | 118.29 | 129.43 | 139.35 | 144.98 | 130.79 | 107.73 | 93.89 |
| $\Pi^{MC}$ | 9.28 | **0.00** | −23.53 | −47.19 | −70.85 | −94.33 | −117.20 | −137.94 | −148.58 | −113.76 | −64.84 | −38.73 |
| $\Pi^{MNC}$ | 233.29 | **234.15** | 235.34 | 235.97 | 236.18 | 235.84 | 234.40 | 229.90 | 212.26 | 142.19 | 72.04 | 38.73 |
| $\Pi^M$ | 242.57 | **234.15** | 211.81 | 188.77 | 165.32 | 141.50 | 117.20 | 91.96 | 63.68 | 28.44 | 7.20 | 0.00 |
| $SW$ | 201.57 | **200.79** | 194.98 | 186.53 | 176.66 | 165.90 | 154.52 | 142.78 | 131.20 | 121.72 | 116.70 | 114.36 |
| $SW^{UW}$ | 318.22 | **317.87** | 312.65 | 304.51 | 294.75 | 283.81 | 271.72 | 257.73 | 237.33 | 192.82 | 152.72 | 133.72 |
| $Reg^*$ | 242.57 | **9.28** | 32.61 | 55.94 | 79.27 | 102.60 | 125.93 | 149.25 | 172.58 | 195.91 | 219.24 | 242.57 |

**Table A-7**
When social welfare equals the unweighted sum of consumer's utility, service providers' profits, and a monopoly's profit with the weight for the non-core profit of 0.5 in the case of congestion and $N = 100$

| | Case 1 | Case 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | 0 | **0** | 0.1 | 0.2 | 0.3 | 0.4 | *0.5* | *0.6* | *0.7* | *0.8* | *0.9* | 1.0 |
| $p_1$ | 53.87 | **24.51** | 20.43 | 16.75 | 13.38 | 10.33 | *51.19* | *55.44* | *55.98* | *56.18* | *56.28* | 56.33 |
| $\tilde{p}_1$ | 55.19 | **26.63** | 22.66 | 19.08 | 15.80 | 12.84 | *52.67* | *56.80* | *57.32* | *57.51* | *57.60* | 57.66 |
| $p_2$ | 97.05 | **98.57** | 98.73 | 98.85 | 98.92 | 98.84 | *91.47* | *91.49* | *91.65* | *91.78* | *91.89* | 91.98 |
| $mc_1$ | 30.00 | **30.00** | 30.00 | 30.00 | 30.00 | 30.00 | *30.00* | *30.00* | *30.00* | *30.00* | *30.00* | 30.00 |
| $mc_2$ | 102.15 | **97.48** | 98.00 | 98.82 | 100.37 | 104.79 | *218.68* | *214.28* | *210.55* | *207.68* | *205.41* | 203.56 |
| $x_1$ | 4.31 | **6.89** | 7.25 | 7.58 | 7.88 | 8.16 | *4.80* | *4.41* | *4.36* | *4.33* | *4.32* | 4.31 |
| $x_2$ | 5.11 | **4.87** | 4.90 | 4.94 | 5.02 | 5.24 | *10.93* | *10.71* | *10.53* | *10.38* | *10.27* | 10.18 |
| $U$ | 21.32 | **28.83** | 30.54 | 32.21 | 33.88 | 35.65 | *55.05* | *53.49* | *51.97* | *50.80* | *49.89* | 49.15 |
| $\Pi^S$ | 3.85 | **9.85** | 10.92 | 11.93 | 12.89 | 13.82 | *4.78* | *4.04* | *3.94* | *3.90* | *3.87* | 3.86 |
| $\Pi^{MC}$ | 88.88 | **0.00** | −24.37 | −48.86 | −73.38 | −97.34 | *97.72* | *100.60* | *100.40* | *100.17* | *99.96* | 99.78 |
| $\Pi^{MNC}$ | 234.79 | **242.88** | 243.66 | 244.28 | 244.59 | 243.36 | *−195.43* | *−167.66* | *−143.44* | *−125.21* | *−111.06* | −99.78 |
| $\Pi^M$ | 323.67 | **242.88** | 219.30 | 195.43 | 171.21 | 146.01 | *−97.72* | *−67.06* | *−43.03* | *−25.04* | *−11.11* | 0.00 |
| $SW$ | 231.44 | **160.13** | 138.93 | 117.42 | 95.69 | 73.81 | *59.84* | *74.30* | *84.60* | *92.26* | *98.19* | 102.90 |
| $SW^{UW}$ | 348.83 | **281.57** | 260.76 | 239.57 | 217.99 | 195.49 | *−37.88* | *−9.53* | *12.88* | *29.66* | *42.65* | 53.01 |
| $Reg^*$ | 323.67 | **88.88** | 112.36 | 135.84 | 159.32 | 182.80 | *206.28* | *229.75* | *253.23* | *276.71* | *300.19* | 323.67 |

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