Simulations of fixed closure and real-time closure to manage migratory fish species for data-limited fisheries

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Highlights

- We compared real-time closure and fixed closure of fisheries in simulations.
- Performance of real-time closure is better than fixed closure in all scenarios.
- Real-time closure is effective even with greater uncertainty of species movement.
- The total closure period can be reduced by applying real-time closure.

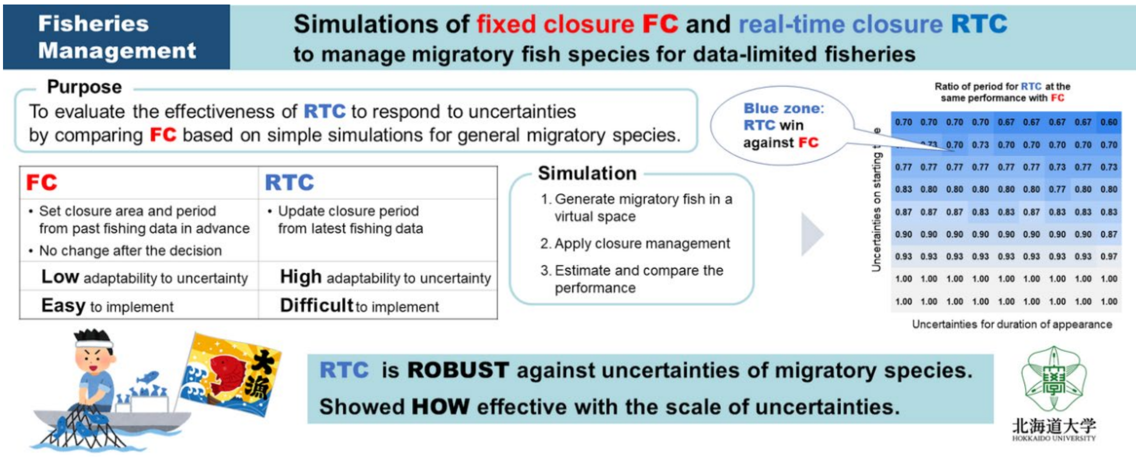
Abstract

Fisheries closure has been used as a fisheries management tool to protect species that need to be conserved. A commonly used type is fixed closure (FC), which specifies the closure area and period in advance and does not change after that decision is made. It has been claimed that FC is not effective for the management of migratory species, because it is difficult for FC to respond to uncertainties in the predicted distribution of species. Recently, real-time closure (RTC) has been introduced to address this issue. However, the use of RTC is still limited, because its benefits compared with FC have not been evaluated sufficiently. In this study, we conducted simple simulations to evaluate the efficiency of RTC to respond to uncertainties in the movement of migratory species. In terms of the protection of migratory species, the mean performance index of RTC was generally higher than that of FC, and the mean performance index of FC tended to decrease with greater uncertainty of species movement. We also estimated the extent of the reduction of the closure period by applying RTC instead of FC. The results of this study indicate that RTC is an efficient method of fisheries closure, and provide quantitative information to guide the use of RTC instead of FC.

Key words: Real-time closure (RTC), Fixed closure (FC), Migration, Data-limited fisheries

Abbreviations: FC, fixed closure; MSE, management strategies evaluation; RTC, real-time closure

Graphical Abstract



1. Introduction

Fisheries closure is a popular fisheries management strategy for the conservation of fish stocks. It prohibits the use of specified fishing vessels and gear in a specified area or period of closure (Ichinokawa et al., 2015; Miethe et al., 2014). It has been used for various purposes, including the conservation of fish stock and the protection of habitats (Hilborn et al., 2004). The closure period for pelagic migratory species that need to be conserved is decided on the basis of aspects of the life cycle such as spawning area and season, and the migration pattern. The selection of an appropriate closure period can maximize the conservation effect.

Fixed closure (FC) is widely applied in fisheries management (Breen et al., 2015; Little et al., 2015; Yagi et al., 2010). In FC, the closure area and period are decided in advance, and they are not changed once that decision is made. The use of FC is effective for some fisheries, especially those for which important areas for conservation, such as the spawning area, are very limited (Diamond et al., 2010; Vinther and Eero, 2013).

However, there are large uncertainties when predicting the migration area and period of migratory species. The actual migration area and period are affected by many factors, including climate change (Kanamori et al., 2019; Peer and Miller, 2014; Punzón and Villamor, 2009). Therefore, there are sometimes mismatches between the FC season and the actual migration of a species through a particular area. Consequently, FC may not protect a migratory species effectively (Dunn et al., 2016; Woods et al., 2018).

Real-time closure (RTC) has attracted attention recently as it is better suited to dealing with uncertainties in the predicted area and migration period of migratory species (Little et al., 2015; O'Keefe et al., 2014). In RTC, a high-catch area can be closed immediately on the basis of the latest real-time catch data. Since technological innovations have made it easier to collect and share real-time data, RTC has become an increasingly viable option (Eliasen and Bichel, 2016; Lewison et al., 2015). In fact, RTC using vessel monitoring system (VMS) data has been already applied in the USA and some European countries (Bethoney et al., 2013; Gullestad et al., 2015; Little et al., 2015; Needle and Catarino, 2011). It has been recognized to be an effective management tool for fisheries in the temperate zone.

However, the use of RTC is still limited, especially for fisheries that have no or limited data collection schemes (Maxwell et al., 2015). Real-time catch data collection is costly, and it can take a long time to establish a data collection scheme (Hobday et al., 2014). To justify the establishment of data collection schemes for RTC, its effectiveness should be evaluated in advance, although this usually requires large spatiotemporal datasets (Dunn et al., 2016, 2011; Hobday and Hartmann, 2006).

Recently, management strategies evaluation (MSE) using simulations has been widely conducted to provide quantitative evidence for selecting appropriate fisheries management strategies (Harlyan et al., 2019; Punt et al., 2016). However, no previous studies have used quantitative information to compare the effectiveness of RTC and FC to manage species with uncertain predicted migration patterns.

The aims of this study were to prove the effectiveness of RTC to respond to uncertainties in the predicted areas and periods of migratory species, and to propose quantitative information to justify a change to RTC from FC on the basis of simple simulations for general migratory species.

2. Methods

2.1 Simulation overview

In these simulations, it is assumed that individuals move on a line at a fixed speed, for simple representation (Fig. 1) (Le Quesne and Codling, 2009; Watson et al., 2019). The fishing ground is defined as the segment in the line. A time step is the duration in which an individual passes through the fishing ground. The period when fish appear in the fishing ground is defined as the appearance period. The closure performance is defined by the proportion of individuals passing through the fishing ground during the closure period out of the total number of individuals on the line.

2.2 Simulation model

The number of individuals in the fishing ground in a given time step t (N_t) is assumed to be constant during the aggregated fish pass across the fishing ground:

$$N_t \sim \begin{cases} \dfrac{N}{l+\varepsilon'} & \text{for } \delta' \leq t \leq \delta' + l + \varepsilon' \\ 0 & \text{for } t < \delta' \text{ or } \delta' + l + \varepsilon' < t \end{cases}$$

where N is the total number of fish, l is the length of fish appearance period in the fishing ground, and δ and ε are random numbers from a truncated normal distribution to describe the uncertainties in the beginning and length of appearance period, respectively. Other assumptions about the number of individuals in the fishing ground were tested and the results are shown in the supplementary materials (Fig. A.1). Recruitment and natural mortality were not considered in these simulations.

The beginning and length of the appearance period were decided by using the truncated normal distribution for describing migration uncertainty:

$$\delta \sim \left\{ \frac{1}{m} N\left(0,\ \left(\frac{l \times \alpha_\delta}{z((1-m)/2)} \right)^2 \right) \right. \quad (-\,l \times \alpha_\delta \leq \delta \leq l \times \alpha_\delta)$$

$$\varepsilon \sim \left\{ \frac{1}{m} N\left(0,\ \left(\frac{l \times \alpha_\varepsilon}{z((1-m)/2)} \right)^2 \right) \right. \quad (-\,l \times \alpha_\varepsilon \leq \varepsilon \leq l \times \alpha_\varepsilon)$$

where *m* is the parameter for truncation (0.95), *z* is the normal equivalent deviation (i.e., $z(0.025) \cong$ 1.96), and α_δ and α_ε are the scales of the uncertainties. The effect of the parameter sets (Table 1) on the results are discussed later. One thousand iterations were conducted to consider the uncertainty of the timing of migration.

α_δ and α_ε are the arbitrary scale of uncertainty, δ and ε are converted to an integer by rounding off the value as follows:

$$\delta' = \mathrm{floor}(\delta + 0.5)$$

$$\varepsilon' = \mathrm{floor}(\varepsilon + 0.5)$$

In these simulations, the duration of the FC was $t = 0$ to l; and the RTC started at $t = \delta' + 1$ and ended at $t = \delta' + 1 + \lambda$. As default, $\lambda = l$.

2.3 Performance indexes

The performance indexes for FC (ω_{FC}) and RTC (ω_{RTC}) were calculated as follows:

$$\omega_{\mathrm{FC}} = \sum_{t=0}^{l} N_t \,/ N$$

$$\omega_{\mathrm{RTC}} = \sum_{t=\delta'+1}^{\delta'+1+\lambda} N_t / N$$

where λ is the length of the RTC $(0 < \lambda \leq l)$. As defined in these simulations, the RTC starts at $t = \delta' + 1$ and ends at $t = \delta' + 1 + \lambda$. To compare performance between RTC and FC, the performance index ratio ($\omega_{\mathrm{RTC/FC}}$) was calculated as follows:

$$\omega_{\mathrm{RTC/FC}} = \frac{\omega_{\mathrm{RTC}}}{\omega_{\mathrm{FC}}} = \frac{\sum_{t=\delta'+1}^{\delta'+1+\lambda} N_t}{\sum_{t=0}^{l} N_t}$$

2.4 Required period ratio

Additional simulations for RTCs with changing λ were conducted. Among the RTCs, the specific RTC with the period that minimized the difference in mean performance index compared with that of FC was defined as the SRTC. The required period ratio (φ) was defined as the ratio of the period for the SRTC (λ_{SRTC}) divided by l, which is the fixed closure period of FC.

$$\varphi = \frac{\lambda_{\mathrm{SRTC}}}{l}$$

If $\varphi = 1$, then the RTC can achieve the same performance as the FC with the same duration of the closure.

The difference in the standard deviation of the performance index ($\sigma_{\mathrm{SRTC-FC}}$) was calculated by subtracting the standard deviation of the performance index of the SRTC (σ_{SRTC}) from that of the FC (σ_{FC}).

3. Results

Figure 2 shows the performance index ratio ($\omega_{\mathrm{RTC/FC}}$) as affected by α_δ and α_ε. The range and mean of $\omega_{\mathrm{RTC/FC}}$ tended to increase with larger α_δ. The mean $\omega_{\mathrm{RTC/FC}}$ at α_δ= 0.8 was 1.61-times higher than that at $\alpha_\delta = 0$. The performance ratio $\omega_{\mathrm{RTC/FC}}$ was almost 1.0 for any value of α_ε.

Figure 3 shows the frequencies of ω_{FC} and ω_{RTC} values. The frequency of ω_{FC} above 90% was

199 out of 1000 iterations, while that of ω_{RTC} above 90% was 624 out of 1000 iterations. Furthermore, the frequency of ω_{FC} below 50% was 224 times out of 1000 iterations, but ω_{RTC} always exceeded 50%.

The required period ratio φ was lower than 1.00 when α_{δ} exceeded 0.2 (Fig. 4). The results were also affected by α_{ε}, depending on its value. When the uncertainties had the highest values (α_{δ}= 0.8, α_{ε}=0.8), φ was 0.6.

The value of $\sigma._{\mathrm{SRTC-FC}}$ was negative across the entire scale of uncertainties (Fig. 5).

4. Discussion

In this study, the effectiveness of RTC to respond to uncertainties in the appearance of migratory species was evaluated by comparing it with FC in simulations. Most previous studies on RTC have examined the effectiveness of empirical or conventional RTC (Dunn et al., 2014; Woods et al., 2018). Dunn et al. (2016) conducted simulations to estimate the performance of RTC and FC in the management of Atlantic cod fisheries by analyzing past high-resolution fishing data. However, to our knowledge, no previous studies have evaluated the performance of RTC and FC in simulations with a scale of uncertainties in the appearance period of migratory species. In this study, we attempted to evaluate the effectiveness of RTC to conserve migratory species with uncertain timing of appearance by using simple simulations. In addition, we aimed to clarify the period required for an RTC to show the same performance as an FC.

4.1 Effectiveness of RTC for migratory species with uncertain timing of appearance

In these simulations, RTC was more effective than FC for conserving migratory species with uncertain timing of appearance (Fig. 2). On the basis of the results of the minimum $\omega_{\mathrm{RTC/FC}}$ obtained in this study, the performance of RTC was almost equal to or greater than that of FC. Especially, RTC had much better performance than FC at larger α_{δ}.

The $\omega_{\mathrm{RTC/FC}}$ was almost stable at any value of α_{ε} (Fig. 2b). This was attributed to the features of the RTC applied in this study. We assumed that the closure period was constant. Therefore, it was difficult for even RTC to deal with uncertainties in the length of the appearance period.

4.2 Quantitative information to change RTC from FC

The frequency of ω (Fig. 3) can be used to establish a quantitative management goal. As a precautionary approach is widely encouraged to establish robust management strategies (Charles, 1998; de Bruyn et al., 2013), policy makers must consider the risks of irreversible damage to fisheries resources. Using the simulations described in this study, policy makers can easily estimate the risks and the probability of success of FC or RTC. The frequency of ω with other scales of uncertainties in other scenarios are included in the supplemental materials (Fig. B.1, Fig. B.2, Fig. B.3).

In this study, we explored the potential for RTC to reduce the total closure period, which allowed us to roughly estimate the economic benefits of RTC. Fisheries closure management should also consider economic losses from reducing the catch of other valuable species (Diamond et al., 2010; Game et al., 2009; Grantham et al., 2008). Applying RTC rather than FC may increase benefits by reducing the duration or area of the closure while meeting conservation objectives (Armsworth et al., 2010; Maxwell et al., 2015). However, RTC has the economic trade-off between the benefits of reducing the closure and the cost of introduction (Hobday et al., 2014; Little et al., 2015; Maxwell et al., 2015). This quick estimation will be useful for policy makers to decide whether or not to introduce RTC.

4.3 Model assumptions

The parameter value of the appearance period, l, was determined at 30 time-steps in these simulations, but the value did not substantially affect the results. The ω_{FC} and ω_{RTC} were mainly determined by the percentage of the appearance period within the closure, and they were estimated by changing the scales of uncertainties (α_{δ} and α_{ε}) in these simulations.

In the default scenario, N_t was assumed to be constant during the aggregated fish pass across the fishing ground. Other assumptions were also tested, as shown in the supplemental materials. In scenarios 2 and 3, aggregated fish were assumed to be concentrated in the center of their distribution. The difference between scenarios 2 and 3 was kurtosis of the distribution of aggregated fish. In scenario 2, the maximum difference of the mean $\omega_{\mathrm{RTC/FC}}$ from that of the default scenario was within 5% (Fig. 2, Fig. A.2). In scenario 3, the maximum difference of the mean $\omega_{\mathrm{RTC/FC}}$ from that of the default scenario was 10.9%, when α_{δ} = 0.8. (Fig. 2, Fig. A.2). However, except for the result at α_{δ} = 0.8, the difference in the mean $\omega_{\mathrm{RTC/FC}}$ between the default scenario and scenario 3 was also within 5%. Therefore, the results were not be greatly affected by the assumptions of the default scenario.

In this study, we focused only on uncertainties in appearance arising from movement, and we removed other biological processes that could be included in MSE simulations. The parameters and model structure for biological processes such as recruitment and natural mortality are varied because of several factors including climate change and environmental variations, and have large uncertainties (Hill et al., 2007; Punt et al., 2014). Thus, the simulations in this study were for a short-term period, so that interannual biological processes did not have to be considered.

Conclusions

In conclusion, the simulations in this study proved the effectiveness of RTC to respond to uncertainties in the appearance time of migratory species, and clarified the scale of uncertainties at which RTC is more effective than FC. This study proposed quantitative information to compare FC with RTC.

The practical use of RTC is still limited. It will be difficult to use RTC to manage fisheries that lack a reliable data collection scheme, because there are no methods to evaluate RTC in advance. However, RTC might be more useful for data-limited fisheries for which there are insufficient long term catch data to formulate an effective FC (Breen et al., 2015). It might be difficult to apply these findings directly to real fisheries situations, but the results of these simulations will be useful to expand the practical use of RTC to conserve several fisheries, including data-limited fisheries.

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Table 1. Parameter set for simulations; l is the length of the appearance period without uncertainties, m is the parameter for truncation, and α_δ and α_ε are the scales of uncertainties for the beginning and length of the appearance period.

Parameter	**Value**
l	30
m	0.95
α_δ	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8
α_ε	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8

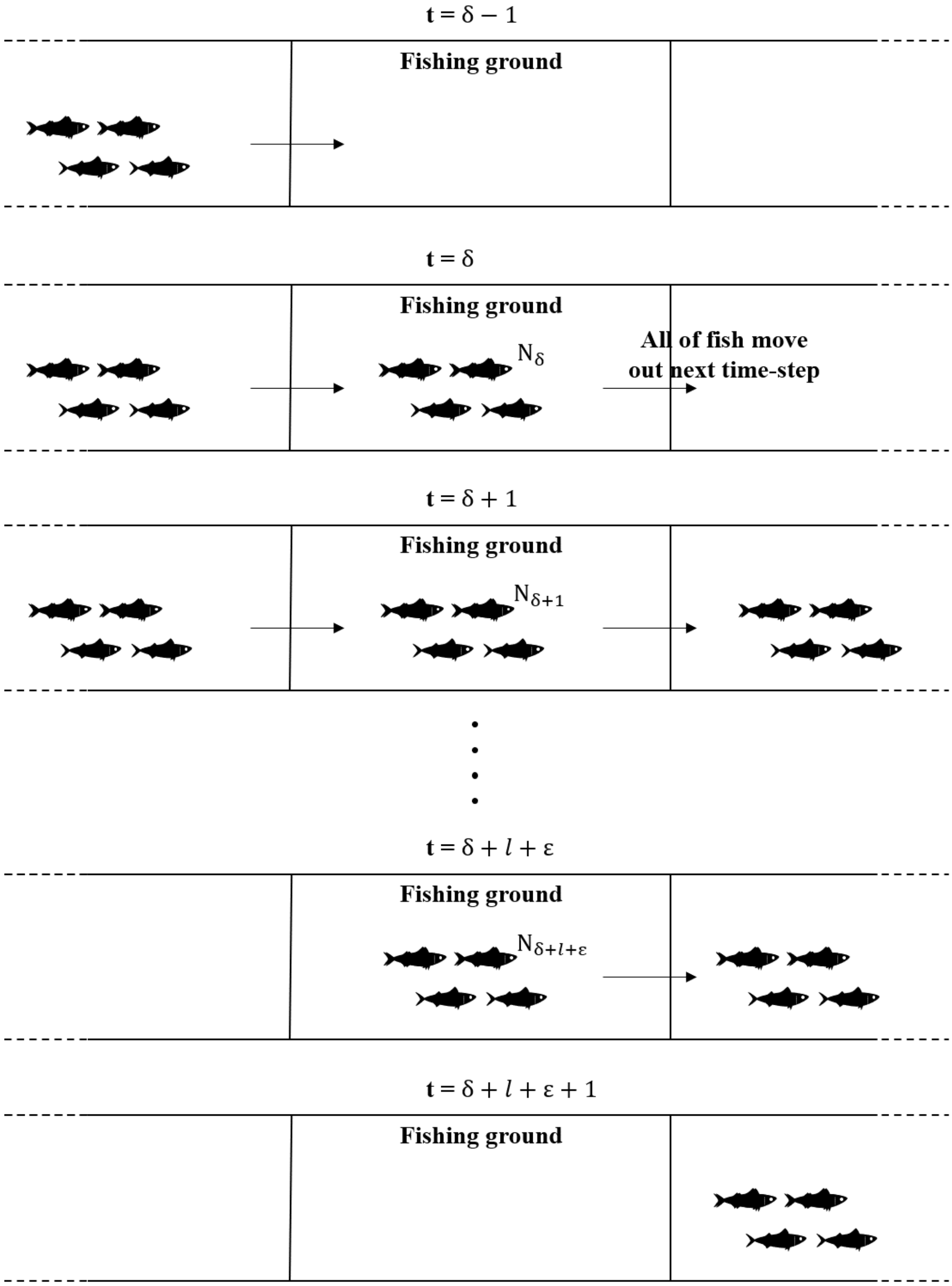

Fig. 1. Representation of space for these simulations. Fishing ground is represented by a segment in the line.

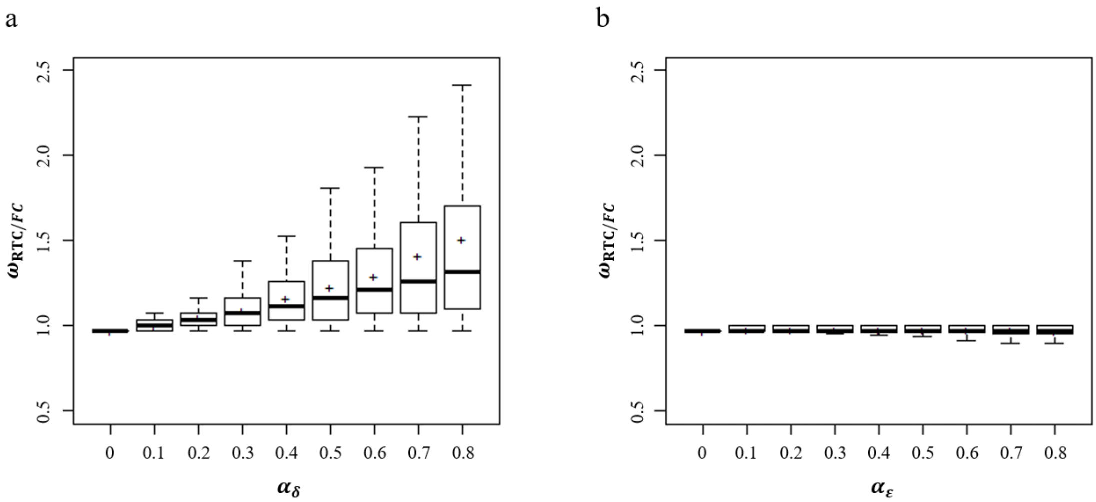

Fig. 2. Performance index ratio ($\omega_{\mathrm{RTC/FC}}$) for each scale of uncertainties in the beginning (a) and period length (b) of the appearance period. Lower and upper box boundaries show 25$^{\mathrm{th}}$ and 75$^{\mathrm{th}}$ percentiles. Line inside box shows median, (+) indicates mean. Lower and upper error lines are largest value within 1.5-times interquartile range above 75$^{\mathrm{th}}$ percentile and smallest value within 1.5-times interquartile range below 25$^{\mathrm{th}}$ percentile, respectively.

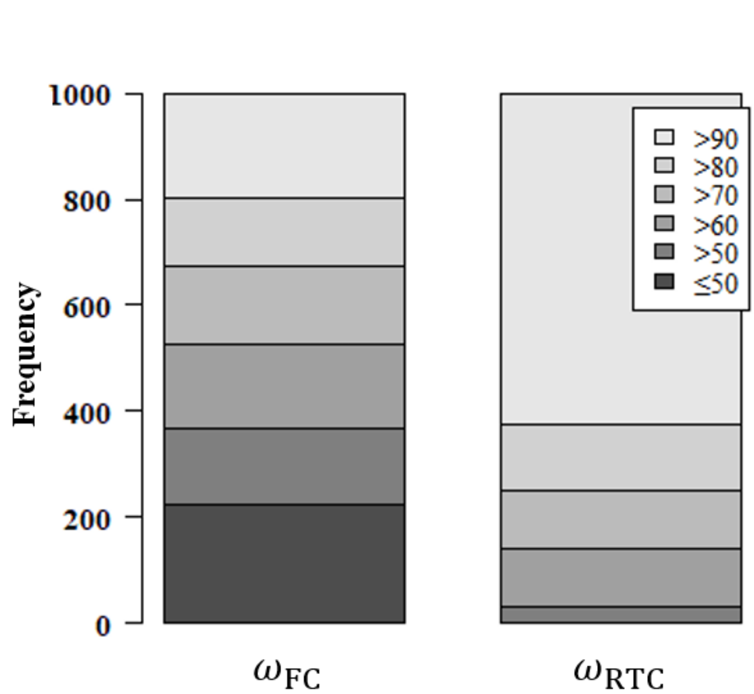

Fig. 3. Frequency of each performance index at largest scale for both uncertainties in 1000 trials (α_{δ}= 0.8, α_{ε}=0.8).

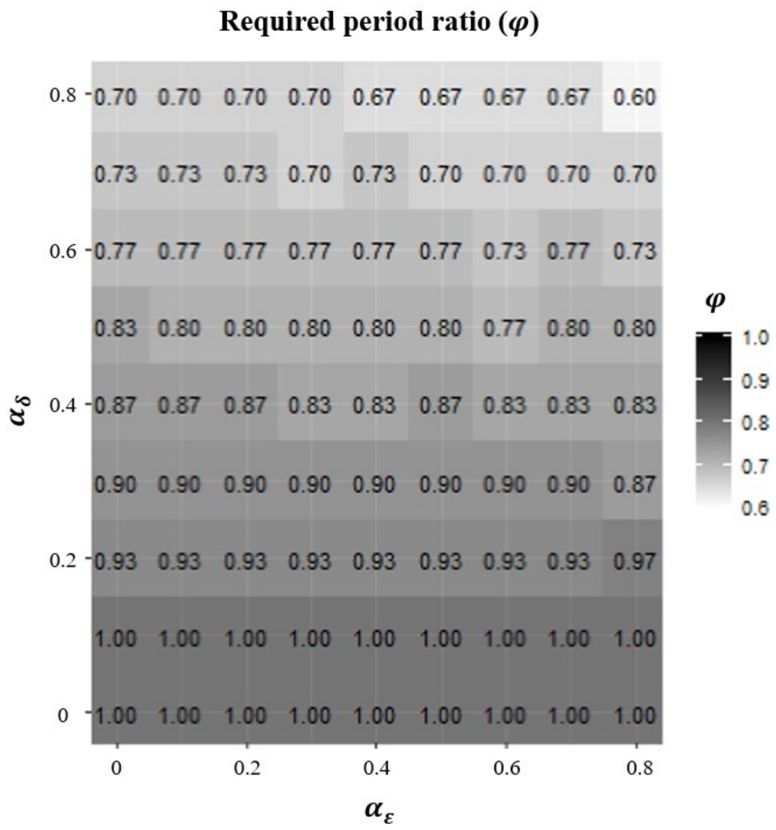

Fig. 4. Required period ratio (φ).

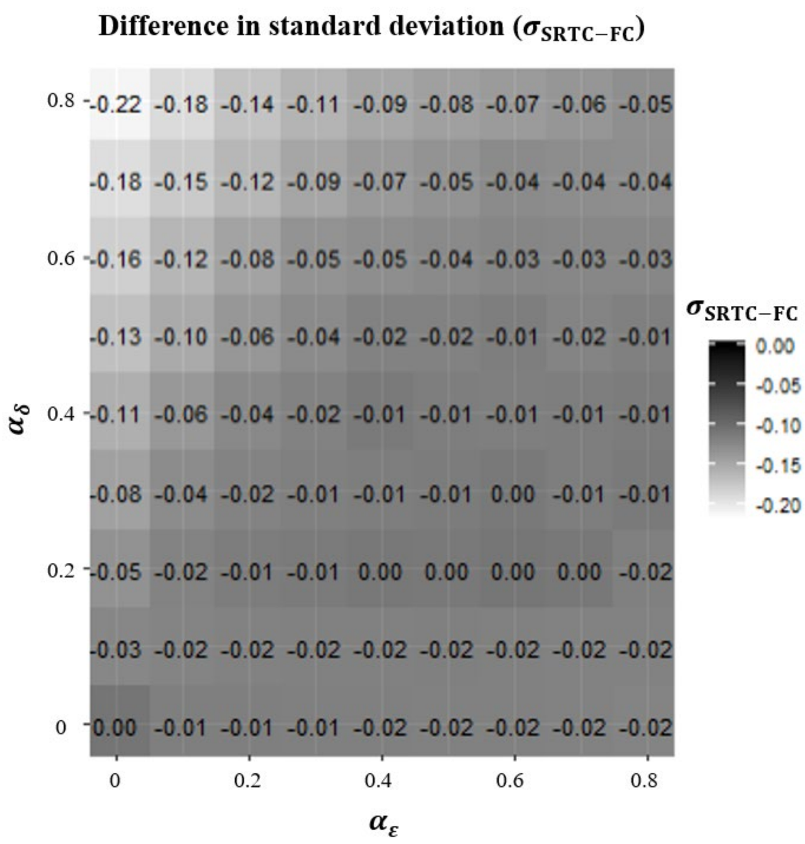

Fig. 5. Difference in standard deviation of performance index between SRTC and FC ($\sigma_{SRTC-FC}$).