Optimization of tuna shing logistic routes through information sharing policies: A game theory-based approach

Groba, Carlos and Sartal, Antonio and Bergantiños, Gustavo

Universidade de Vigo

11 November 2019

Optimization of tuna fishing logistic routes through information sharing policies: A game theory-based approach

Carlos Groba (cgroba@uvigo.es)

School of Economics and Business, Rúa Leonardo Da Vinci, s/n.
Campus das Lagoas/Marcosende, 36310, Spain

University of Vigo

Antonio Sartal (antoniosartal@uvigo.es)*

Faculdade de Ciencias e Tecnologia da Universidade Nova de Lisboa,
Campus Universitario, Caparica 2829-516, Portugal

University of Vigo/ New University of Lisbon

Gustavo Bergantiño Cid (gbergant@uvigo.es)

School of Economics and Business, Rúa Leonardo Da Vinci, s/n.
Campus das Lagoas/Marcosende, 36310, Spain

University of Vigo

***Corresponding author:**

Antonio Sartal

Faculdade de Ciencias e Tecnologia da Universidade Nova de Lisboa,

Campus Universitario, Caparica 2829-516, Portugal

e-mail: antoniosartal@unidemi.com, antoniosartal@uvigo.es

Optimization of tuna fishing logistic routes through information sharing policies: A game theory-based approach

Abstract

The tuna fishing industry's increasing regulatory restrictions on the number of FADs per vessel is forcing companies to rethink their fishing practices to ensure their continued profitability. Despite these expanding constraints, and although many studies have been published on the use of FADs and their implications, to date there has been little research on how to help the tuna fishing industry optimize its procedures. Based on real data and using the game theory approach, we suggest a new collaborative method of employing FADs that involves their use between vessels, and we demonstrate that sharing FADs optimizes the use of fuel and time for entire fleets. Our findings show that, with the correct incentives, all stakeholders, including the company, the skipper, and even the environment, can achieve mutually improved results by sharing information.

Keywords

FAD restrictions, Tuna fishing industry, Economic incentives for sharing, Fuel consumption reduction, Game theory, Sustainability

1 Introduction

The performance of the tropical tuna fishing industry is, more than ever, bound to the use of drifting fish aggregating devices (FADs), the use of which has become widespread since 1991 (Ariz, Delgado, Fonteneau, Gonzales Costas, & Pallarés, 1992). With the scope of new regulations affecting the tuna industry, this paper furnishes a study from a perspective that prioritizes efficiency, imposing the theoretical framework of game theory.

The global tuna fishery is one of the largest in the world. The most widely used and fastest-growing fishing gear for targeting tuna is the purse seine (PS). Tropical PS started to operate in the Atlantic Ocean in the 1960s and were introduced into the Indian Ocean in the early 1980s. PS fishers principally target skipjack tuna (*Katsuwonus pelamis*, Scombridae) schools, but also schools of small juvenile bigeye (*Thunnus obesus*, Scombridae) and yellowfin tuna (*Thunnus albacares*, Scombridae) (Phillips et al., 2017). These species tend to gravitate toward objects floating on the surface of the ocean (Castro, Santiago, & Santana-Ortega, 2001; P. Fonteneau & Pianet, 2000). The aggregate behavior of tuna toward floating objects was first observed in the context of tuna interacting with natural floating objects (FOBs) emerging from river mouths. Aiming to simulate FOBs, fishermen started deploying large numbers of their own FOBs. These human-made drifting FADs generally consisted of bamboo, stabilized in the surface currents by large pieces of netting hanging below; these early FADs were able to stay adrift for up to two months (Ménard, Stéquert, Rubin, Herrera, & Marchal, 2000). It is worth noting here that there are two kind of FADs: anchored FADs, or *Payaos*, and drifting FADs. This study refers exclusively to drifting FADs (FADs).

The tuna fishing industry targets a mixture of free-swimming schools (FS) and of drifting FAD schools. The main advantage of FADs for fishers is that they increase the catchability of tuna, relative to sets on FS (Guillotreau, Salladarré, Dewals, & Dagorn, 2011). Even fleets that have traditionally relied on FS sets are moving towards FAD-based strategies (Lopez, Moreno, Sancristobal, & Murua, 2014). The increasing use of FADs resulted in subsequent increases in PS catches per unit effort (CPUE) over time (A. Fonteneau, Chassot, & Bodin, 2013; Griffiths, Allain, Hoyle, Lawson, & Nicol, 2019; Maufroy et al., 2016). In parallel, the extensive use of FADs by the PS fishery industry increases the possibility of a number of negative impacts, including a reduction in yield per recruitment of two target tuna species (bigeye and yellowfin), increased bycatch and perturbation of the pelagic ecosystem balance, and alteration of the normal movements of the species associated with FADs (Bromhead, Foster, Attard, Findlay, & Kalish, 2003; P. Fonteneau & Pianet, 2000; Holmes, Hanich, & Soboil, 2019); such effects, however, are difficult to estimate with any accuracy (Lopez et al., 2014). From a research perspective, there is reason to be hopeful; although, at present, FADs are only used for fishing purposes, they can also serve scientific objectives (Brehmer et al., 2019; Moreno et al., 2016).

Be that as it may, due to the increased use of FADs, recent efforts from regional fisheries management organizations (RFMOs) have given rise new regulations on the number of FADs that each PS can manage. These increasing regulatory restrictions, in conjunction with other constrains that affect Global marine fisheries (e.g., those aimed at minimizing bycatch and discards (Escalle et al., 2019)), force companies to rethink their fishing practices and optimize the use of FADs to ensure their profitability. With these newly implemented restrictions, it is essential that the tuna fishing industry rethinks their fishing practices and optimize the use of FADs to ensure continued profitability.Although many studies have been published regarding the use of FADs and their implications, little research exists on how to help the tuna fishing industry optimize its fishing practices (Groba, Sartal, & Vázquez, 2015, 2018).

In this context, our work describes a new way for tuna fishing companies to employ FADs that involves sharing them between vessels, and we demonstrate that sharing FADs maximizes fuel efficiency and use of time, while decreasing CO_2 emissions across entire fleets. First, with a foundation in game theory and, in particular, the well-being assessment, two different theoretical mechanisms were developed: one without compensation and the other with compensation. The first mechanism (without compensation) explains why many vessels do not like sharing FADs, and the second mechanism (with compensation), shows an equilibrium where all vessels want to share FADs. Second, this theoretical approach is evaluated empirically with real data through simulations, and the expected result emerges: There is a situation in which all players, including the company and skippers, win, proving that best-route optimization occurs when the information gleaned from FADs is shared between vessels. Data for this study come from different groups of tuna vessels retrieving their FADs in the Indian Ocean during April 2017.

The paper is organized as follows: The next section provides a review of the literature. Section 3 describes the game theory approach; Section 4 introduces the data, the experimental design and discusses the results; and finally, Section 5 concludes by highlighting the paper's main contributions and implications.

2 Background

The use of FADs by PS has evolved over the years to improve fishing efficiency. The FAD itself has undergone improvements in shape, materials, and net length, both to drift with the currents of interest and also to minimize the risk of entangling turtles, sharks, and other non-targeted species (Filmalter, Capello, Deneubourg, Cowley, & Dagorn, 2013). FADs have also evolved technologically. From the beginning, the use of artificial FADs has relied on tracking buoys to know where the FADs are. The first buoys were radio-based, and each vessel used secret frequencies to locate its own floating objects (Ménard et al., 2000). In 1996, GPS buoys with a virtually unlimited range appeared on the market and positively affected the size of fishing areas (Morón, Areso, & Pallares, 2001).

During the 2000s, satellite technologies, including Inmarsat D+ and Iridium SBD, became affordable alternatives to the buoys (Moreno, Dagorn, Sancho, & Itano, 2007). The use of satellite communications was a revolution for the tuna fishing industry because, although each buoy had a monthly airtime fee, satellite communication technology brought many advantages, relative to the previous-radio-based buoy technology. These advantages included the ability to receive FAD positions at any distance and to change the configuration of the buoys from the vessel. Remote detection of satellite-tracked FADs often allows purse seiners to move directly toward a buoy, even at night, avoiding, or significantly reducing the time once required to actually search for and locate the buoys by sight (Gaertner et al., 2016). Further, satellite buoys did not use large carbon antennas for transmission like the radio buoys did. As such, satellite buoys were difficult to detect by radar, making them less likely to be stolen, which was a big advantage over radio buoys. In any case, most FADs are easily identified by other vessels due to the birds that are so frequently positioned above the FADs and identifiable, even at great distances, by bird radars. This phenomenon accounts for the majority of FAD losses for a given owner, which are due to appropriation by other fishing vessels (around 50% of the FADs in the Indian ocean) (Moreno et al., 2018). Finally, satellite communication technology provided vessels the capacity to share their FADs' positions with other vessels, allowing vessels to collaborate with the aim of improving their fishing efficiency.

The last major improvement to the buoys was the development of echo-sounders, which were introduced around 2008 to monitor the amount of biomass aggregated beneath the FAD (Lopez et al., 2014). This new technological device reduced the searching time (i.e., enables remote identification of FADs with associated tunas) and provided new information for fishers to learn more about the location and behavior of tuna and other associated species. Several indicators suggest that echo-sounder buoys may be as important or more important than other significant technological developments in the fishery industry, such as the introduction of sonar in the vessels (Lopez et al., 2014).

The echo-sounder technology embedded in the buoy was a game-changer for the tropical tuna industry, in terms of optimization. Before this improvement, PS traveled from FAD to FAD, searching for tuna. After the introduction of the echo-sounder tuna buoys, they only traveled to FADs that had fish beneath, which improved their fishing efficiency by potentially saving time and fuel and by discovering new fishing areas. The latest improvements to echo-sounder technology are aiming toward an ability to discriminate among tuna species (Moreno, Boyra, Sancristobal, Itano, & Restrepo, 2019).

Consequently, there was an increasing acquisition of FADs by PS. For example, in the Atlantic Ocean (A. Fonteneau, Chassot, & Gaertner, 2015), the total number of FADs increased 730%, from $1,175$ FADs active in January 2007 to $8,575$ in August 2013. In the Indian Ocean this number increased 458%, from $2,250$ FADs in October 2007 to $10,300$ FADs in September 2013 (Maufroy et al., 2016). This increase has resulted in regulation from RFMOs of the number of FADs that a PS can manage, for example, in the Indian Ocean, where the number of FADs, as defined in Resolution 19/02, will be no more than 300 active instrumented buoys and 500 annual acquisitions of instrumented buoys per vessel (IOTC circular 2019). Currently, this limitation is also being imposed in the Atlantic Ocean through the International Commission for the Conservation of Atlantic Tunas (ICCAT), and all indicators predict that the Pacific Ocean will follow the same initiative via the Inter-American-Tropical-Tuna-Commission (IATTC) (P. Fonteneau & Pianet, 2000), as well as the Western & Central Pacific Fisheries Commission (WCPFC).

It is noteworthy that skippers have important economic incentives, depending on how many tons they fish, but it should also be acknowledged that FAD fishing currently represents their unique way of increasing catches (especially of skipjack) due to existent limitations on the free schools catches. Meanwhile, tuna fishing companies or firms pay these incentives with, aiming to maximize the number of fished tons of the whole company. The costs of the entire fleet are assumed by the firm, including salaries, goods, and fuel, among other expenses.

In terms of fishing management and efficiency, Salas and Gaertner (2004) showed how essential it is for effective management to know the dynamics of the fisheries. Bez, Walker, Gaertner, Rivoirard, and Gaspar (2011) used a vessel monitoring system (VMS) to measure tuna fishing efforts to study and quantify the spatial dynamic of the tropical tuna PS fishing activity. In terms of fuel consumption, Parker, Vázquez-Rowe, and

Tyedmers (2015) analyzed fuel performance and the carbon footprint of the global PS tuna fleet. Meanwhile Hospido and Tyedmers (2005) employed life cycle assessment (LCA) to quantify the scale and importance of emissions that result from the range of industrial activities associated with contemporary Spanish PS fisheries. Gaertner and Dreyfus-Leon (2004) analyzed the shape of the relationship between CPUE and abundance in a tuna PS fishery, using a simulation that hinged on artificial neural networks. In terms of fuel consumption efficiency, Groba et al. (2015) showed how important it can be to optimize the route of a tuna vessel retrieving FADs. In the case of tropical tuna fishery efficiency, the literature is scarce. For this reason, and with recent RFMO regulations in mind, the proper use of FADs by tuna vessels is a matter of great importance for tuna fisheries.

In this paper, the behaviors of tuna fishing vessels that use FADs are studied for the first time from the point of view of game theory. Indeed, through real-data simulations, this paper shows that there are policies changing the way that tuna vessels work with FADs. If tuna fishing companies settle into capitalizing on the opportunities provided by new policies, they may see improvements in their overall efficiency.

3 The tuna fishing vessels problem: A game theory approach

3.1 The tuna fishing vessels problem

Tuna skippers may be driven by important economic incentives that are directly dependent on how many tons they fish. Such incentives also depend on the tuna ton price (Jeon, Reid, & Squires, 2008). Because of this, it is important for skippers to maximize the number of tons fished; the more a vessel fishes in less time, the better. Depending on the season and the ocean, purse seiners can target either FADs or free-swimming schools (FS), but skippers usually prefer a high probability of positive sets with small catches (typical with FADs) to a low probability of positive sets with higher catches (typical with FS) (Floch et al., 2012; Guillotreau et al., 2011; Lopez et al., 2015; Squires & Kirkley, 1999). It is important to note the geographical movement pattern of FADs over time, where some of them can move outside the potential fishing zone of the vessel or the entire PS fleet. A tuna vessel faces, for instance, an optimization problem that hinges on determining which route to follow using its FADs, which are drifting in the ocean and in its fishing zone (Groba et al., 2015).

We suppose that FS fishing can happen at any moment a vessel detects birds via radar or some other sign of a fishable free-swimming school. This, however, is something we cannot predict. Nevertheless, optimizing the route to retrieve a company's FADs also offers vessels the same opportunities to FS fishing as any other non-optimal FAD retrieval strategy.

Each vessel is limited to a certain number of FADs it can use to fish (Moreno et al., 2018). This limit depends on the RFMO that has authority over the area in which the tuna vessel belongs. A tuna vessel may share its FAD's information among groups of two to five vessels, depending on the size of the company (Groba et al., 2018). It should be noted that, usually, each company has several vessels (ranging from two or three to ten or more). In fact, more than 94% of the European companies that operate in the Indian Ocean have two or more vessels [1]. In these cases, FADs are shared among the group of fishing vessels, and incentives are shared as well. Groups of vessels that fish together are also sharing confidences, which is one reason they are typically small.

By contrast, firms want to maximize the overall company profits, which means that vessels have to fish as much as they can and that variable costs, such as fuel, crew costs, and equipment must be minimized. This also requires the optimization of the fishing of n vessels (vessels that the firm owns) with m FADs (the sum of FADs from all the vessels of the company).

In most of the practical cases, the costs associated with vessels (like fuel, which is the one we consider) are paid by the firm. Besides, the skipper has a salary that can be increased by bonuses that depend on the amount of tuna fished. Thus, the utility of the firm depends directly on the amount of tuna fished and the fuel cost. Nevertheless, the utility of the skipper depends directly on the amount of tuna fished but not on the fuel cost (which is also paid by the firm). Given these circumstances, the direct incentives for fuel cost minimization are associated with the firm but not with the skippers. Facing this situation, a new scenario for analysis and improvement appears, hinging on how to maximize the profits for all agents. The aim of this paper is to study this equilibrium in detail, with real data and explain how and why tuna fisheries currently operate. Further, this paper presents a new proposal, centered on FAD-sharing policies, which shows improvements for both individual and collective performance and reduction of CO_2 emissions.

3.2 A game theory approach

We introduce a theoretical model to facilitate the study of the previously described problem. We considered two different mechanisms by which the firm can incentive vessels to share FADs. When vessels share FADs, the total distance traveled by all vessels is reduced, which produces cost savings for the firm. Our analysis was conducted through a non-cooperative game with incomplete information, following the model of Aumann (1976), which we believe is the most suitable for this case. We also consider the Bayesian Nash equilibria (BNE) (Nash, 1951), the most standard solution for these types of games (Harsanyi, 1967).

Let $N = \{1, \ldots, n\}$ the set of tuna vessels, briefly, vessels. We assume that all vessels work for the same firm, which we denote by f.

There is a finite number of FADs (or buoys) that have been assigned to the vessels following some criteria. We assume that each FAD is assigned to a single vessel. Thus,

[1] Information extracted from IOTC Record of Authorised Vessels: https://www.iotc.org/vessels

each vessel $i \in N$ has an initial endowment $b_i = \left\{\left(b_i^k\right)\right\}_{k=0}^{n_i} = \left\{\left(x_i^k, y_i^k\right)\right\}_{k=0}^{n_i}$. The interpretation is the following: Vessel i has been assigned to handle n_i FADs $\left\{b_i^1, \ldots, b_i^{n_i}\right\}$. The position of each FAD k with $k = \{1, \ldots, n_i\}$ is given by $\left(x_i^k, y_i^k\right)$ where x_i^k denotes the latitude and y_i^k the longitude. We further denote by $b_i^0 = \left(x_i^0, y_i^0\right)$ the position of vessel i at the beginning of the process. We also assume that FADs are numbered in the order of their recovery by vessel i. Namely, vessel i is located in position $\left(x_i^0, y_i^0\right)$. Thus, it moves to FAD b_i^1 and recovers the tuna in that FAD. Next, vessel i moves to position FAD b_i^2 and so on.

Therefore, we make the following assumptions:

- Each vessel knows the position of all FADs to which has been assigned. No vessels know the location of the FADs assigned to other vessels.
- In the theoretical model, we assume that each vessel incurs a cost c per mile traveled between FADs. This cost is paid by the firm. In our simulations, we compute c by assuming that the average vessel speed is 15 knots. Thus, we estimate a fuel cost of \$29 US per nautical mile to travel between FADs.
- Vessels cannot know in advance the amount of tuna they will find at each FAD. We denote by q the expected amount of tuna by FAD. We denote by q_i^k the amount of tuna recovered by skipper i in FAD b_i^k. These amounts can be known only after fishing.

  In our simulations we take $q = 6.1$ tons for every skipper i and every FAD b_i^k. This value supposes that a tuna vessel fishes, on average, 9.000 tons per year, works 295 days during the year and visits 5 FADs per working day. Nevertheless, any other quantity of tons per FAD can be used in the simulations.
- Each vessel i cannot know in advance the amount of time t_i^k it will take to recover the tuna of FAD b_i^k.

  In our simulations, we assume that t_i^k is 3 hours for every vessel i and every FAD b_i^k.
- Each vessel i can also fish tuna by free schools (FS) or by the poaching of others' FADs. Let $fs(b_i)$ denote the amount of tuna vessel i obtains by FS when it is trying to recover FADs in b_i.

  Similarly, let $po(b_i)$ denote the amount of tuna vessel i obtains by FS or FADs poaching when it is trying to recover its own FADs in b_i.

  In the Appendix, we will prove that our results hold, independently of the values of the fishing in FS or FAD poaching. Thus, for the sake of simplicity, in our simulations we assume that both are 0.
- Each skipper receives a price p corresponding to each amount of tuna fished.

  In our simulations, we consider several values for p.

Once vessel (skipper) i has recovered all of its FADs, the utility obtained is computed as the amount fished, multiplied by the price paid by the firm. Namely,

$$p\left(\sum_{k=1}^{n_i} q_i^k + fs(b_i) + po(b_i)\right)$$

The utility of the firm is

$$(p_f - p)\left(\sum_{i=1}^{n}\sum_{k=1}^{n_i} q_i^k + \sum_{i=1}^{n} fs(b_i) + \sum_{i=1}^{n} po(b_i)\right) - c\sum_{i=1}^{n} d\left(b_i\right)$$

where $d\left(b_i\right)$ is the distance traveled by vessel i to recover all FADs in b_i. Namely, the firm pays a unit price of p to every vessel and sells the fish at the price p_f. Additionally, the firm must pay costs associated with the travel of the vessels.

As usual, the game theoretical model considers direct utilities, which can be measured objectively. Of course, the firm and the skippers may have other incentives that do not appear in our model: the welfare of the crew, the CO_2 emissions, the profitability of the vessel and the firm, and so on. Since the fuel cost is paid by the firm, skippers do not have a direct incentive to share their FADs to minimize the distance traveled. Nevertheless, the firm has incentives to incentivise the skippers to do this. If the fuel cost is reduced, then the total utility of the firm will be increased.

We consider two possible mechanisms by which firms can induce skippers to share their FADs. We model such mechanisms as two games with incomplete information following Aumann's model. Additionally, we study the Bayesian Nash equilibria (BNE) of both games, which provide predictions of the behavior of rational agents when facing such situations.

In the Appendix, we theoretically study both mechanisms, and we formally present the games to model both mechanisms. We also compute the BNE associated with both mechanisms (Propositions 1 and 2).

For now, we present the results in a more informal way. The basic idea of both mechanisms is the same. First, the vessels or skippers decide independently whether they want to share their FADs. If a vessel refuses to share, then this vessel fishes with its own FADs. For the vessels that agree to share, the firm redistributes their FADs among the cooperating vessels. Next, every vessel fishes in its reassigned FADs.

Mechanism 1: Reassigning FADs without compensation. The firm pays the skippers according to the FADs each vessel has been assigned. Suppose that vessel i initially had 20 FADs, decided to share its FADs, and was reassigned to 18 FADs. The firm pays skipper i according to the amount of fish obtained by the 18 reassigned FADs. If vessel i is reassigned to the same or more FADs than it initially had, then vessel i is also paid according to the number of assigned FADs.

In Proposition 1 of the Appendix, we theoretically study this mechanism. Here we discuss the practical implications of Proposition 1. According to part (a), if each vessel decides not to share its FADs (as in Example 2 of the Appendix), then we have a BNE, and the firm cannot save in fuel. In other cases (as in Example 1 of the Appendix), there may exist a different BNE, wherein some vessels share FADs and the firm saves fuel costs.

By part (b) of Proposition 1, we realize that the utility of each skipper i in any BNE will always be the same and coincide with the utility skipper i obtains when it does not share FADs. This result is independent of the number of FADs, the position of the FADs, and the information the vessels have on the position of the FADs. Thus, skipper i does not have an incentive to share its FADs under any circumstance, because skipper i cannot improve its expected utility by sharing instead of not sharing. If skipper i shares its FADs, it may be the case that skipper i receives more FADs than it initially had, but it may also receive less. The average will be the same.

Our theoretical results prove that under this mechanism, skippers do not have incentives to share their FADs under any circumstance. This helps explain why tuna vessels work alone or in small groups. Nevertheless, this mechanism is not the most beneficial for the firm.

Mechanism 2: Reassigning FADs with compensation. The firm offers a guarantee to skippers who share their FADs to pay, at minimum, in accordance with the original number of FADs the vessel was assigned. For example, suppose that vessel i initially had 20 FADs, decided to share its FADs, and is reassigned with 18 FADs. The firm pays skipper i the same amount that vessel i would have received if it had recovered 2 more FADs. If vessel i is reassigned with the same or more FADs than it initially was assigned, it will be paid according to the number of reassigned FADs.

In Proposition 2 of the Appendix, we theoretically study this mechanism. Here, we discuss the practical implications of Proposition 2. According to part (a), we know that there is a BNE when every skipper decides not to share its FADs. The same applies to Mechanism 1. Per part (c), there is also a BNE when every skipper shares its FADs and the firm reorganizes all the FADs optimally. Further, the utility of the firm and each skipper under part (c) is greater than or equal to when no vessels share FADs.

We then asked the following: when is the BNE of part (c) different from that of part (a)? We also sought to determine the extent of these differences. In Example 3 of the Appendix, both BNE are essentially the same. Thus, from a theoretical point of view, the answer to our question is that it depends on the characteristics of the problem. We then offered (in the next section) a practical answer to both questions. After developing simulations based on real data, our results showed that, in all cases studied, the BNE of part (c) was different from that of part (a). Additionally, both were quite different in terms of utility obtained by the skippers and the firm. In this case, the firm clearly benefits more than the skippers.

Part (b) of Proposition 2 says the following: Suppose that skipper i decides between sharing or not sharing its FADs. Independent of the position of its FADs or the decision taken by other skippers, the expected utility obtained by sharing its FADs is never smaller than the expected utility obtained by not sharing its FADs. This means that the Bayesian Nash equilibria we should observe, in practice, is the one in which every skipper shares its FADs. Thus, with Mechanism 2, every skipper has incentives to share its FADs, and this mechanism is also suitable for the firm.

4 Data and results

In this section, we articulate a design for an experiment that, based on data from the movement of FADs, assesses the theoretical propositions made in the previous section. It is worth recalling that we used real data from different tuna fishing companies. To test our model exclusively for scientific purposes, Marine Instruments provided us with anonymous real data from several tuna vessels fishing in the FAO[2] capture zone no. 51 (Eastern Indian Ocean) from April 9 to April 23, 2017. Figure 1 shows the FAO no. 51 area (in red) and the area of real data provided by Marine Instruments (in green).

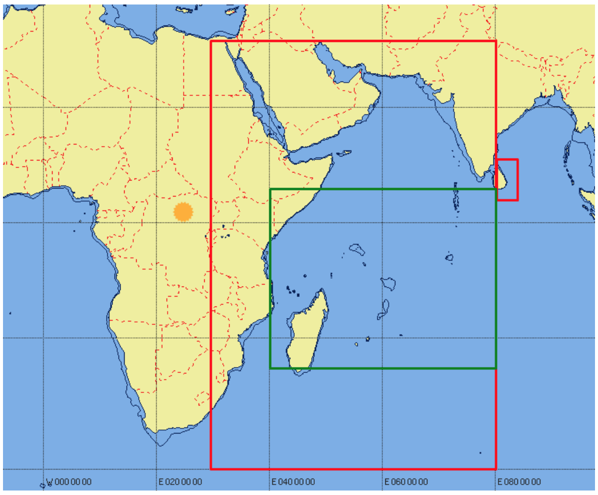

Figure 1: Experiment design

It is worth emphasizing here three key issues regarding our sample. On the one hand, although in free-school fishing, there appear to be some months that are more favorable, fishing with FAD does not present the same seasonal disparity (A. Fonteneau et al. (2013); Maufroy et al. (2016)). On the other hand, we regard a month of study as a sufficient time period since it is a fairly common fishing period (Groba et al., 2015).

Finally, regarding the number of boats, our data sample comes from a tuna fishing company composed of 3 vessels (i.e., 3 skippers) with 20 FADs per vessel. The decision to use 3 boats has a dual purpose: first, it is one of the most common ways to work the tuna vessels; second, it was the simplest (and most parsimonious) way to approach

[2]Food and Agriculture Organization of the United Nations

our objective: "demonstrate the potential to share." Furthermore, it is worth recalling that the chosen conditions are intended to represent the most demanding conditions, as the potential savings generated derive from fuel savings (Groba et al. (2015); Groba et al. (2018)). As these authors point out, these savings grow when fishing campaigns increase (i.e., higher number of FADs) and with greater distribution complexity (i.e., with a greater number of vessels).

This information was gathered randomly using the MSB software, a platform for receiving and visualizing buoy data, from Marine Instruments. We performed 10 measurements in each experiment, varying the positions of the FADs and the vessels, to obtain representative mean values for each case study. We suppose that tuna vessels navigate at 15 knots and, for simplicity, the expected average of tuna by FAD is 6.1 tons[3], with \$29 per nautical mile the cost of fuel at this speed. All these working conditions are represented in Table 1 and were obtained from Marine's historical records for vessels working in this area during the last decade:

Table 1: Experiment assumptions

Description	**Value**
Number of vessels	3
FADs per vessel	20
Vessel speed	15 knots
Fishing time	3 hours
Tons beneath each FAD	6.1
Cost per ton	\$1,400
Fuel cost per mile	\$29
Skipper benefit	10%

It should also be noted that, for correct interpretation of the results, all skippers have variable benefits that depend on the quantity of fish they catch. While this value may be different from one company to another, we have supposed an average benefit of about 10% of the total amount of tuna fished, which is based on the average tuna stock price. Although the companies did not give us this information, they confirmed that the supposed percentage is a reasonable value. Of course, this value should be used with caution, given wide variability of tuna prices across species, as well as over the course of the year or in different years. We also want to note that this percentage does not affect our qualitative results (namely, both the company and the skippers attain more benefits with this new procedure). For the sake of simplicity, we paid no attention to the firm's fixed expenditures, such as crew costs, supplies, fishing licenses, etc.

Considering these conditions and following the same structure as in the previous

[3] We try to study the decision of the skipper in some moment of the time, given the information the skipper has at such moment. We assume that the skipper knows the number of FADs to which has been assigned but cannot know in advance the amount of tuna at each FAD. Thus, we consider that the amount of tuna of each FAD is 6.1 tons, the expected average.

theoretical section, a total of three different scenarios were considered. The first scenario (Table 2) describes the current situation in which the skippers do not share their FADs. In the second scenario (Table 3), the three skippers share the FADs without compensation. Finally, in the last scenario (Table 4), the same situation is proposed, but with compensation for the skippers to share. Next, each of these three situations is analyzed in detail.

In the first scenario, we assumed that the skippers did not share their FADs. In these conditions, therefore, each skipper only knows the position of their own FADs. The results obtained are shown in Table 2, where we can observe the money earned by each skipper (vessel) and the money earned by the firm (owner of the three tuna vessels) within the conditions (tons per FAD, cost per ton, fuel cost, etc.) previously illustrated in Table 1. To obtain a representative average value (Avg.), we have repeated each simulation 10 times to represent different FADs situations. It is worth recalling that we assume the same quantity of fish beneath each FAD. Therefore, the expected amount of money earned for each skipper is the same for each simulation, but it is not for the firm, because totals also depend on how many miles the vessels navigate, and the firm's benefits depend not only on the amount of tuna captured, but also on the fuel spent; the more miles traveled, the fewer benefits for the firm.

Table 2: Current way of working: Vessels do not share their FADs

	Skipper 1	**Skipper 2**	**Skipper 3**	**Ship owner**
1	\$ 16,969	\$ 16,969	\$ 16,969	\$ 248,267
2	\$ 16,969	\$ 16,969	\$ 16,969	\$ 247,448
3	\$ 16,969	\$ 16,969	\$ 16,969	\$ 244,741
4	\$ 16,969	\$ 16,969	\$ 16,969	\$ 255,185
5	\$ 16,969	\$ 16,969	\$ 16,969	\$ 255,032
6	\$ 16,969	\$ 16,969	\$ 16,969	\$ 256,515
7	\$ 16,969	\$ 16,969	\$ 16,969	\$ 258,642
8	\$ 16,969	\$ 16,969	\$ 16,969	\$ 255,185
9	\$ 16,969	\$ 16,969	\$ 16,969	\$ 244,166
10	\$ 16,969	\$ 16,969	\$ 16,969	\$ 251,943
Avg.	\$ 16,969	\$ 16,969	\$ 16,969	\$ 251,712

In the second scenario (Table 3), we assume that the three skippers (vessels) agree to share their FADs, so the firm makes an optimal distribution of the FADs and assigns them in a smart way from the office to the vessels. This means that, sometimes, one vessel can have 20 FADs, sometimes more and sometimes less. Table 3 shows these results, and we can observe that skippers 1 and 2 achieve greater benefits than skipper 3 because, on average, they had more FADs during the simulations.

In this scenario, the firm would obtain important benefits because of the fuel saved by this smart distribution of FADs, reaching 8.5% improvement compared to the previous scenario. However, the total benefits of the skippers does not change. Skipper 1 improves

4.3%, skipper 2 improves 0.8% but skipper 3 decreases 5.1% (compared to Table 1, which reflects current fishing methods). These results confirm the theoretical results we have seen in the previous section. Skippers have no direct incentives to share their FADs with other vessels because the expected benefit of a skipper who shares his FADs is the same as that of a skipper who doesn't share his FADs. Thus, as there is no expectation of improvement, it seems very likely that the skippers would not want to take risks and continue working only with their own FADs. Seen from the global point of view of the company (and shareholders), however, the best scenario would involve sharing. Our empirical results corroborate the theoretical assumptions described above and help explain why many tuna vessels work alone. Nevertheless, this mechanism is not the most suitable for the firm.

Table 3: Mechanism 1: Reassigning FADs without compensation

	Skipper 1	**Skipper 2**	**Skipper 3**	**Ship owner**
1	$ 17,818	$ 16,121	$ 16,970	$ 281,716
2	$ 17,818	1 $ 6,970	$ 16,121	$ 266,843
3	$ 19,515	$ 15,273	$ 16,121	$ 269,936
4	$ 16,970	$ 16,970	$ 16,970	$ 276,557
5	$ 17,818	$ 16,121	$ 16,970	$ 285,337
6	$ 16,970	$ 18,667	$ 15,273	$ 258,980
7	$ 17,309	$ 18,723	$ 14,877	$ 269,586
8	$ 17,164	$ 19,063	$ 14,683	$ 270,121
9	$ 19,515	$ 16,121	$ 15,273	$ 279,064
10	$ 16,121	$ 16,970	$ 17,818	$ 272,243
Avg.	$ 17,702	$ 17,100	$ 16,107	$ 273,038
Diff	4.3%	0.8%	-5.1%	8.5%

In the third scenario, the firm changes its strategy of incentives for the skippers, as shown in Proposition 2 (see Mechanism 2: Reassigning FADs with compensation in Section 3). In this scenario, the firm guarantees pay to vessels that share FADs, at least according to the number of FADs the vessel initially had. In other words, when a skipper has fewer FADs assigned than the average, he or she is automatically compensated by the firm. For example, when a skipper has 2 FADs fewer than would otherwise have been the situation (i.e., 20), the company will still pay for 20 FADs, so there is not any risk for the skipper. However, when the skipper has more FADs assigned than the average (for instance, 21), he or she will keep them, fishing more, and the quantity of fish expected for each vessel will be more than in the first scenario. With this policy of incentives, it seems logical to expect the bosses to be encouraged to collaborate since everybody wins. In fact, as was theoretically proved in Proposition 2, every skipper has incentives to share his/her FADs; therefore, the Bayesian Nash equilibria we should observe in practice with real-data is the one in which every vessel shares its FADs.

Results in Table 4 show that each skipper enjoys more benefits than in the first scenario, where the skipper did not share, and the firm also earns more than in the first scenario, although less than in the second, as expected. The simulations performed thus bear out the theoretical predictions described in the previous section, validating, with real data, the benefits of this new procedure.

Table 4: Mechanism 2: Reassigning FADs with compensation

	Skipper 1	**Skipper 2**	**Skipper 3**	**Ship owner**
1	$ 17,818	$ 16,969	$ 16,969	$ 280,867
2	$ 17,818	$ 16,969	$ 16,969	$ 265,994
3	$ 19,515	$ 16,969	$ 16,969	$ 267,390
4	$ 16,969	$ 16,969	$ 16,969	$ 276,557
5	$ 17,818	$ 16,969	$ 16,969	$ 284,488
6	$ 16,969	$ 18,666	$ 16,969	$ 257,283
7	$ 17,309	$ 18,723	$ 16,969	$ 267,492
8	$ 17,163	$ 19,062	$ 16,969	$ 267,834
9	$ 19,515	$ 16,969	$ 16,969	$ 276,518
10	$ 16,969	$ 16,969	$ 17,818	$ 271,394
Avg.	$ 17,786	$ 17,524	$ 17,054	$ 271,582
Diff	4.8%	3.3%	0.5%	7.9%

We used the nearest neighbor strategy to recover FADs during the simulations. This means that FAD distribution was based on assigning FADs closer to each tuna vessel. This is a quick and sound distribution method, commonly used by the tuna industry at present, but it is far from optimal. The result may be improved further if this recovery strategy changed to adapt to the dynamic nature of drifting FADs, as is shown in Groba et al. (2018). In this case, it was proved that the quantity of miles traveled could be reduced by 21.4% in the case of 3 vessels and 20 FADs per vessel in comparison with the NN strategy, as we use in our approach. It not only indicates that the firm earns more, due to the route optimization, but also that fishing time will be reduced, so skippers can fish the same quantity in less time and still gain all the associated economic and environmental benefits.

5 Conclusions

Taking our data into account, this paper proposes a new, coordinated way of working for the tuna fishing companies related to FAD collection. Situated within the well-known framework of game theory, our findings reflect the value of sharing FADs. We demonstrate that, with the correct incentives, there is a situation in which all stakeholders, including the company, skipper, and even the environment, obtain better results. Further, global economic profits are realized for the fleet and company, and CO_2 emissions are reduced.

From a scholarly perspective, our work provides empirical evaluation using real data and it supports and applies the adequacy of the proposed theoretical model –a non cooperative game with incomplete information following the model of Aumann and considering Bayesian Nash equilibria– to a complex, real-world situation. We assumed two different situations: 1) reassigning FADs without compensation and 2) reassigning FADs with compensation. While in the first situation, our results only corroborate theoretical assumptions (and explain why tuna vessels work alone), the empirical portion of the second situation complements the previous theoretical section. While, theoretically, we could only predict that it was favorable to share FADs, the simulations performed allow us to confirm this and verify that both the company and the skippers get more benefits with this new procedure. Additionally, with our data, we can also estimate how much more they each earn on average over time. We can therefore confirm that this mechanism is suitable for the firm.

As the firm will enjoy savings due to the route optimization, tuna vessels will reduce their fishing time and fuel consumed. In addition, fuel reduction presents another important advantage: increased storage capacity. Benefits of sharing information between vessels could inspire other non-tuna fisheries that are exploiting large fishing zones. This paper opens up, therefore, a set of possibilities for a wide range of real-world problems.

Similarly, from a policy maker's perspective, our work addresses a new, more-efficient way to work with increasing FAD regulations regarding the number of FADs per PS. These regulations were first introduced in the Indian Ocean by the Indian Ocean Tuna Commission (IOTC) with Resolution 19/02, they have since been extended to the rest of the RFMOs (IATTC, ICCAT and WCPFC). It is essential, therefore, for the tuna fishing industry to optimize the use of FADs. As it seems clear that this number will be drastically reduced in the next few years, there is no other way but to use them as efficiently as possible.

From an environmental perspective, our proposal would directly reduce the total current CO_2 emissions. This is a significant improvement, as climate change is one of the main problems facing humanity today (Howard-Grenville, Buckle, Hoskins, & George, 2014). In addition, the development of more sustainable fishing methods using FADs may be possible because of our research.

Acknowledgements

The authors wish to thank Marine Instruments for the buoy data. The authors are partially supported by research grants ECO2016-76625-R and ECO2017-82241-R from the Spanish Ministry of Science and Competitiveness, GRC 2014/021, GRC 2015/014 and ED431B 2019/34 from "Xunta de Galicia".

References

Ariz, J., Delgado, A., Fonteneau, A., Gonzales Costas, F., & Pallarés, P. (1992). Logs and tunas in the eastern tropical atlantic. a review of present knowledge and uncertainties. In *Proceedings of the international workshop on fishing for tunas associated with floating objects, la jolla, ca* (pp. 21–65).

Aumann, R. (1976). Agreeing to disagree. *Annals of Statistics*, *4*, 1236–1239.

Bez, N., Walker, E., Gaertner, D., Rivoirard, J., & Gaspar, P. (2011). Fishing activity of tuna purse seiners estimated from vessel monitoring system (vms) data. *Canadian Journal of Fisheries and Aquatic Sciences*, *68*(11), 1998–2010.

Brehmer, P., Sancho, G., Trygonis, V., Itano, D., Dalen, J., Fuchs, A., ... Taquet, M. (2019). Towards an autonomous pelagic observatory: experiences from monitoring fish communities around drifting fads. *Thalassas: An International Journal of Marine Sciences*, *35*(1), 177–189.

Bromhead, D., Foster, J., Attard, R., Findlay, J., & Kalish, J. (2003). *A review of the impact of fish aggregating devices (fads) on tuna fisheries: Final report to the fisheries resources research fund.* Bureau of Rural Sciences Canberra.

Castro, J. J., Santiago, J. A., & Santana-Ortega, A. T. (2001). A general theory on fish aggregation to floating objects: an alternative to the meeting point hypothesis. *Reviews in fish biology and fisheries*, *11*(3), 255–277.

Escalle, L., Gaertner, D., Chavance, P., Murua, H., Simier, M., Pascual-Alayón, P. J., ... Mérigot, B. (2019). Catch and bycatch captured by tropical tuna purse-seine fishery in whale and whale shark associated sets: comparison with free school and fad sets. *Biodiversity and conservation*, *28*(2), 467–499.

Filmalter, J. D., Capello, M., Deneubourg, J.-L., Cowley, P. D., & Dagorn, L. (2013). Looking behind the curtain: quantifying massive shark mortality in fish aggregating devices. *Frontiers in Ecology and the Environment*, *11*(6), 291–296.

Floch, L., Delgado de Molina, A., Assan, C., Dewals, P., Areso, J., & Chassot, E. (2012). Statistics of the european purse seine fishing fleet and associated flags targeting tropical tunas in the indian ocean (1981-2011). In *Iotc working party on tropical tunas.*

Fonteneau, A., Chassot, E., & Bodin, N. (2013). Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (dfads): Taking a historical perspective to inform current challenges,ãÜ. *Aquatic Living Resources*, *26*(1), 37–48.

Fonteneau, A., Chassot, E., & Gaertner, D. (2015). Managing tropical tuna purse seine fisheries through limiting the number of drifting fish aggregating devices in the atlantic: food for thought. *Collect. Vol. Sci. Pap. ICCAT*, *71*(1), 460–475.

Fonteneau, P., & Pianet. (2000). A worldwide review of purse seine fisheries on fads.

Gaertner, D., Clermidy, S., Ariz, J., Bez, N., Moreno, G., Murua, H., ... Marsac, F. (2016). Results achieved within the framework of the eu research project: Catch, effort, and ecosystem impacts of fad-fishing (cecofad). *Acta Agriculturae Slovenica.*

Gaertner, D., & Dreyfus-Leon, M. (2004). Analysis of non-linear relationships between catch per unit effort and abundance in a tuna purse-seine fishery simulated with artificial neural networks. *ICES Journal of Marine Science*, *61*(5), 812–820.

Griffiths, S. P., Allain, V., Hoyle, S. D., Lawson, T. A., & Nicol, S. J. (2019). Just a fad? ecosystem impacts of tuna purse-seine fishing associated with fish aggregating devices in the western pacific warm pool province. *Fisheries Oceanography*, *28*(1), 94–112.

Groba, C., Sartal, A., & Vázquez, X. H. (2015). Solving the dynamic traveling salesman problem using a genetic algorithm with trajectory prediction: An application to fish aggregating devices. *Computers & Operations Research*, *56*, 22–32.

Groba, C., Sartal, A., & Vázquez, X. H. (2018). Integrating forecasting in metaheuristic methods to solve dynamic routing problems: Evidence from the logistic processes of tuna vessels. *Engineering Applications of Artificial Intelligence*, *76*, 55–66.

Guillotreau, P., Salladarré, F., Dewals, P., & Dagorn, L. (2011). Fishing tuna around fish aggregating devices (fads) vs free swimming schools: Skipper decision and other determining factors. *Fisheries Research*, *109*(2-3), 234–242.

Harsanyi, J. (1967). Games with incomplete information played by ‚Äòbayesian‚Äô players. *Management Science*, *14 (3)*, 159–182.

Holmes, G., Hanich, Q., & Soboil, M. (2019). Economic benefits of fad set limits throughout the supply chain. *Marine Policy*, *103*, 1–8.

Hospido, A., & Tyedmers, P. (2005). Life cycle environmental impacts of spanish tuna fisheries. *Fisheries Research*, *76*(2), 174–186.

Howard-Grenville, J., Buckle, S. J., Hoskins, B. J., & George, G. (2014). Climate change and management. *Academy of Management Journal*, *57*(3), 615–623.

Jeon, Y., Reid, C., & Squires, D. (2008). Is there a global market for tuna? policy implications for tropical tuna fisheries. *Ocean Development & International Law*, *39*(1), 32–50.

Lopez, J., Fraile, I., Murua, J., Santiago, J., Merino, G., & Murua, H. (2015). *Technological and fisher‚Äôs evolution on fishing tactics and strategies on fads vs. non-associated fisheries* (Tech. Rep.). IOTC–2015–WPTT17–32.

Lopez, J., Moreno, G., Sancristobal, I., & Murua, J. (2014). Evolution and current state of the technology of echo-sounder buoys used by spanish tropical tuna purse seiners in the atlantic, indian and pacific oceans. *Fisheries Research*, *155*, 127–137.

Maufroy, A., Kaplan, D. M., Bez, N., De Molina, A. D., Murua, H., Floch, L., … editor: Jan Jaap Poos, H. (2016). Massive increase in the use of drifting fish aggregating devices (dfads) by tropical tuna purse seine fisheries in the atlantic and indian oceans. *ICES Journal of Marine Science*, *74*(1), 215–225.

Ménard, F., Stéquert, B., Rubin, A., Herrera, M., & Marchal, É. (2000). Food consumption of tuna in the equatorial atlantic ocean: Fad-associated versus unassociated schools. *Aquatic living resources*, *13*(4), 233–240.

Moreno, G., Boyra, G., Sancristobal, I., Itano, D., & Restrepo, V. (2019). Towards acoustic discrimination of tropical tuna associated with fish aggregating devices. *PloS one*, *14*(6), e0216353.

Moreno, G., Dagorn, L., Capello, M., Lopez, J., Filmalter, J., Forget, F., … Holland, K.

(2016). Fish aggregating devices (fads) as scientific platforms. *Fisheries Research*, *178*, 122–129.

Moreno, G., Dagorn, L., Sancho, G., & Itano, D. (2007). Fish behaviour from fishers' knowledge: the case study of tropical tuna around drifting fish aggregating devices (dfads). *Canadian Journal of Fisheries and Aquatic Sciences*, *64*(11), 1517–1528.

Moreno, G., Murua, J., Dagorn, L., Hall, M., Altamirano, E., Cuevas, N., … Restrepo, V. (2018). Workshop for the reduction of the impact of fish aggregation devices', structure on the ecosystem. In *Technical and meeting reports.*

Morón, J., Areso, J. J., & Pallares, P. (2001). Statistics and technical information about the spanish purse seine fleet in the pacific. In *14th meeting of the standing committee on tuna and billfish, noumea, new caledonia* (pp. 9–16).

Nash, J. (1951). Non-cooperative games. *The Annals of Mathematics*, *54 (2)*, 286–295.

Parker, R. W., Vázquez-Rowe, I., & Tyedmers, P. H. (2015). Fuel performance and carbon footprint of the global purse seine tuna fleet. *Journal of Cleaner Production*, *103*, 517–524.

Phillips, J. S., Pilling, G. M., Leroy, B., Evans, K., Usu, T., Lam, C. H., … Nicol, S. (2017). Revisiting the vulnerability of juvenile bigeye (thunnus obesus) and yellowfin (t. albacares) tuna caught by purse-seine fisheries while associating with surface waters and floating objects. *PloS one*, *12*(6).

Salas, S., & Gaertner, D. (2004). The behavioural dynamics of fishers: management implications. *Fish and fisheries*, *5*(2), 153–167.

Squires, D., & Kirkley, J. (1999). Skipper skill and panel data in fishing industries. *Canadian Journal of Fisheries and Aquatic Sciences*, *56*(11), 2011–2018.

Zamir, S. (2013). *Bayesian games: Games with incomplete information. in: Meyers r. (eds) encyclopedia of complexity and systems science.* Springer.

A Appendix

We now introduce some well known concepts of non cooperative game theory. We refer to Zamir (2013) for a detailed discussion of such concepts.

An **Aumann model of incomplete information** (Aumann (1976)) is a tuple

$$\left(I, X, (\pi_i)_{i\in I}, P\right)$$

where I is the set of agents; X is the set of states of the world; for each $i \in I$, π_i is a partition of X; and P is a probability distribution over X (called common prior).

Given $x \in X$ and $i \in I$ we denote by $\pi_i(x)$ the element of π_i to which x belongs to.

The interpretation is as follows. There is a possible set of states of the world (X) and a probability distribution (P) over X known by all agents. An element $x \in X$ is randomly selected according with P. Each agent $i \in I$ has different information about such element, which is given by π_i. We assume that agent i knows that an element of $\pi_i(x)$ has happened, but he/she can not distinguishes among the elements of $\pi_i(x)$.

The Harsanyi's model of incomplete information (Harsanyi (1967) is more popular than the Aumann's model of incomplete information. In this paper we use Aumann's model because it fits better with the problem we are studying.

For each state of the world $x \in X$ we consider the classical non-cooperative game $\Gamma^x = \left(I, (A_i^x)_{i\in I}, (u_i^x)_{i\in I}\right)$ played at this state. For each agent $i \in I$, A_i^x denotes the set of pure actions that agent i can take when the state of the world is x. We assume that $A_i^x = A_i^{x'}$ when $\pi_i(x) = \pi_i(x')$. Besides $u_i^x : \times_{i\in I} A_i^x \to \mathbb{R}$ represents the utility of agent i.

An strategy for agent i is a mapping σ_i assigning to each state of the world $x \in X$ an action $\sigma_i(x) \in A_i^x$ such that $\sigma_i(x) = \sigma_i(x')$ when $\pi_i(x) = \pi_i(x')$. We denote by Σ_i the set of all strategies of agent i.

A Bayesian game on X is a triple $\left(I, (\Sigma_i)_{i\in I}, (u_i)_{i\in I}\right)$ where for each $\sigma = (\sigma_i)_{i\in I}$ and each $i \in N$

$$u_i(\sigma) = \int_X u_i^x\left((\sigma_i(x))_{i\in I}\right) dP$$

A **Bayesian Nash equilibria (briefly BNE)** is a tuple $\sigma = (\sigma_i)_{i\in I}$ such that for for each $i \in I$ and each $\sigma_i' \in \Sigma_i$ we have that $u_i(\sigma) \geq u_i(\sigma \backslash \sigma_i')$ where $\sigma \backslash \sigma_i'$ is the combination of strategies where agent i plays σ_i' and each agent $j \in I \backslash \{i\}$ plays σ_j.

Intuitively, in a BNE at each stage of the world x each agent i is playing a best reply against the strategies of the other agents. Thus, a BNE is an extension of the Nash equilibria (Nash (1951)) to this setting.

We have included free school and poaching in our theoretical model (see section 3.2). As we have mentioned above we are trying to incentivate skippers to share their FADs in such a way that all agents (the skippers and the firm) improve. Skippers must take the decision (to share or not to share) with limited information. A skipper knows its assigned FADS. Besides, the skipper knows that it is possible to obtain more catches by poaching and free schools. What happens if the skipper decides to share? He will obtain other FADS but the possibility of poaching and free school remains. With the new FADs, such possibilities increase, decrease or remain the same? We assume that remain the same because poaching and free schools is something that you can not know in the moment in which the skipper takes the decision.

Suppose that vessel i has been assigned initially with FADs b_i. The skipper of vessel i decides to share and then it is assigned with FADs B_i.

In the initial situation the expected utility of the skipper is

$$p\left(n_i q + fs + po\right)$$

whereas in the case of sharing it is

$$p\left(|B_i| q + fs + po\right).$$

Thus, the fact that the utility in case of sharing is larger or equal than in the initial situation depends only on the FADs part of the utility of the skipper, namely, on $n_i q$ and $|B_i| q$.

Since in a BNE we only compare when the utility of a strategy is larger or equal than the utility of other strategy, we will obtain the same BNE for all possible values of free schools and poaching.

Thus, in order to simplify our technical results, we have decided to take $fs = po = 0$ in the rest of this Appendix.

A.1 Mechanism 1. Reassigning FADs without compensation

We consider the Aumann model of incomplete information $\left(I, X, (\pi_i)_{i\in I}, P\right)$ defined as follows.

- $I = \{f, 1, ..., n\}$ where f is the firm and i denotes vessel i for each $i = 1, ..., n$.

  In our simulations we will take 3 vessels. Namely, $n = 3$.

- X is the set of possible locations of the $\tau = \sum_{i=1}^{n} n_i$ FADs assigned to the vessels. Namely $X = Z^\tau$ where Z denotes the set of places where a FAD can be located. We assume that coordinates 1 to n_1 from Z^τ refer to the position of the FADs assigned to vessel 1. Coordinates $n_1 + 1$ to $n_1 + n_2$ from Z^τ refer to the position of the FADs assigned to vessel 2 and so on. A generic element of X will be denoted as $x = (x_j)_{j=1}^{\tau}$.

In our simulations we take Z as the Indic Ocean. Besides each vessel will have 20 FADs ($n_i = 20$ for all $i \in N$) and hence $\tau = 60$.

- $(\pi_i)_{i\in I}$ model the situation where each vessel only knows the position of its FADs and the firm knows the position of all FADs.

  Given $i \in N$ and $x, x' \in X$ we have that $\pi_i(x) = \pi_i(x')$ if and only if the position of the FADs assigned to vessel i in x and x' are the same. Namely, for each $j = \sum_{k=1}^{i-1} n_k + 1, ..., \sum_{k=1}^{i} n_k$ we have that $x_j = x'_j$.

  For each $x \in X$, $\pi_f(x) = \{x\}$.

- P is a probability distribution over X. We do not consider a specific distribution for P because our theoretical results hold for any P.

The non-cooperative game $\Gamma^x = \left(I, (A_i^x)_{i\in I}, (u_i^x)_{i\in I}\right)$ we consider is defined for modelling the following situation. Each vessel, independently, decides if it share its FADs with other vessels. If a vessel says no, then such vessel remains with the same FADs. Among the vessels that say yes, the firm reassign the FADs of such vessels among themselves. We now formalize this idea.

- I as above.

- $(A_i^x)_{i\in I}$. For each $i \in N$, $A_i^x = \{YES, NO\}$.

  Let $N^{x,YES}$ the set of vessels that says YES. Let

$$B^{x,YES} = \bigcup_{i\in N^{x,YES}} \bigcup_{k=1}^{n_i} b_i^k$$

  be the set of all FADs assigned initially to vessels that said YES.

  A_f^x is the set of all possible reallocations of the FADs of $B^{x,YES}$ among agents in $N^{x,YES}$. Namely,

$$A_f^x = \left\{ \begin{array}{c} (B_i)_{i\in N^{x,YES}} : \text{for each } i \in N^{x,YES},\ \varnothing \subset B_i \subset B^{x,YES}, \\ \bigcup_{i\in N^{x,YES}} B_i = B^{x,YES} \text{ and} \\ B_i \cap B_j = \varnothing \text{ for each } i,j \in N^{x,YES},\ i \neq j. \end{array} \right\}$$

- $(u_i^x)_{i\in I}$. Let $(a_i^x)_{i\in I} \in \times_{i\in I} A_i^x$.

  Let $j \in N$ be a vessel that said NO. Then, the vessel continue with the same FADs, b_j. Hence its utility is $u_j\left((a_i^x)_{i\in I}\right) = pn_jq$.

  Let $j \in N$ be a vessel that said YES. Then, the vessel has a new set of FADs, B_j. Hence its utility is $u_j\left((a_i^x)_{i\in I}\right) = p|B_j|q$ where $|B_j|$ denotes the number of FADs in B_j.

Finally, the utility of the firm is

$$u_f\left((a_i^x)_{i\in I}\right) = (p_f - p)\sum_{i=1}^{n} n_j q - c\sum_{i\in N\setminus N^{x,YES}} d(b_i) - c\sum_{i\in N^{x,YES}} d(B_i)$$

The utility of the firm has three parts. The first one, $(p_f - p)\sum\limits_{i=1}^{n} n_j q$, corresponds to the benefits of selling the fish. This part is independent of the actions taking by the vessels. The second one, $-c\sum\limits_{i\in N\setminus N^{x,YES}} d(b_i)$, corresponds to the cost of the fuel of the vessels that did not share its FADs. This part depends on the actions of the vessels but not on the action of the firm. The third one, $-c\sum\limits_{i\in N^{x,YES}} d(B_i)$, corresponds to the cost of the fuel of the vessels that shared its FADs. This part depends on the actions of the vessels and on the action of the firm.

We now make a theoretical analysis of the Bayesian game $\left(I, (\Sigma_i)_{i\in I}, (u_i)_{i\in I}\right)$ associated to this case.

Proposition 1. Let $\left(I, X, (\pi_i)_{i\in I}, P\right)$ be the Aumann model of incomplete information defined as above.

(a) Let $\sigma = (\sigma_i)_{i\in I}$ be such that for each $i\in N$ and for each $x\in X$, $\sigma_i(x) = NO$. Then, σ is a BNE of $\left(I, (\Sigma_i)_{i\in I}, (u_i)_{i\in I}\right)$ and for each $i\in N$, $u_i(\sigma) = pn_i q$.

(b) Let $\sigma = (\sigma_i)_{i\in I}$ be a BNE of $\left(I, (\Sigma_i)_{i\in I}, (u_i)_{i\in I}\right)$. Then, for each $i\in N$, $u_i(\sigma) = pn_i q$.

Proof of Proposition 1. We first note that for each $i\in I$ and each $\sigma = (\sigma_i)_{i\in I}$ we have that

$$u_i(\sigma) = \int_X u_i^x\left((\sigma_i(x))_{i\in I}\right) dP = \sum_{X_i\in\pi_i}\int_{X_i} u_i^x\left((\sigma_i(x))_{i\in I}\right) dP$$

and $\sigma_i(x) = \sigma_i(x')$ for all $x, x'\in X_i$.

(a) We have to prove that for each $i\in I$ and each $\sigma_i'\in\Sigma_i$, we have that $u_i(\sigma)\geq u_i(\sigma\backslash\sigma_i')$.

Let $i = f$. Since all vessels are saying NO, firm has nothing to do. Then, for each $\sigma_f'\in\Sigma_f$ we have that $u_f(\sigma) = u_f\left(\sigma\backslash\sigma_f'\right)$.

Let $i\in N$ and $\sigma_i'\in\Sigma_i$. Thus,

$$u_i(\sigma\backslash\sigma_i') = \sum_{X_i\in\pi_i}\int_{X_i} u_i^x\left(\sigma_i'(x), (\sigma_j(x))_{j\in I\setminus\{i\}}\right) dP.$$

Let $X_i \in \pi_i$ be such that $\sigma'_i(x) = NO$ for each $x \in X_i$. Since $\sigma_i(x) = NO$ for each $x \in X_i$ we have that

$$\int_{X_i} u_i^x \left(\sigma'_i(x), (\sigma_j(x))_{j \in I \setminus \{i\}}\right) dP = \int_{X_i} u_i^x \left((\sigma_j(x))_{j \in I}\right) dP.$$

Let $X_i \in \pi_i$ be such that $\sigma'_i(x) = YES$ for each $x \in X_i$. Thus, $N^{x,YES} = \{i\}$ and $B^{x,YES} = \bigcup_{k=1}^{n_i} b_i^k$. Hence A_f^x, the set of all possible reallocations of the FADs of $B^{x,YES}$ among agents in $N^{x,YES}$ has a unique element, namely, to assign all the FADs of vessel i to vessel i. Thus,

$$\int_{X_i} u_i^x \left(\sigma'_i(x), (\sigma_j(x))_{j \in I \setminus \{i\}}\right) dP = \int_{X_i} u_i^x \left((\sigma_j(x))_{j \in I}\right) dP.$$

Hence,

$$u_i(\sigma \setminus \sigma'_i) = \sum_{X_i \in \pi_i} \int_{X_i} u_i^x \left((\sigma_j(x))_{j \in I}\right) dP = u_i(\sigma).$$

(b) We first prove a couple of statements that will be used in the proof of this part.

Statement 1. Let $\sigma = (\sigma_i)_{i \in I}$ be a BNE of $\left(I, (\Sigma_i)_{i \in I}, (u_i)_{i \in I}\right)$. Then, there exists $X' \subset X$ such that $\int_{X'} dP = 1$ and for each $x \in X'$, $\sigma_f(x) = (B_i^*)_{i \in N^{x,YES}}$ where

$$\sum_{i \in N^{x,YES}} d(B_i^*) = \min \left\{ \sum_{i \in N^{x,YES}} d(B_i) : (B_i)_{i \in N^{x,YES}} \in B^{x,YES} \right\}.$$

Proof of Statement 1. For each $x \in X$ we denote $\sigma_f(x) = (B_i)_{i \in N^{x,YES}}$. Besides, we define $X'' = \left\{x \in X : \sigma_f(x) \neq (B_i^*)_{i \in N^{x,YES}}\right\}$.

Suppose that the statement does not hold. Then, $\int_{X''} dP > 0$.

We now define σ'_f such that $\sigma'_f(x) = (B_i^*)_{i \in N^{x,YES}}$ for all $x \in X$. Then

$$\begin{aligned} u_f(\sigma \setminus \sigma'_f) &= \int_X u_f^x \left(\sigma'_f(x), (\sigma_j(x))_{j \in I \setminus \{f\}}\right) dP \\ &= \int_{X \setminus X''} u_f^x \left(\sigma'_f(x), (\sigma_j(x))_{j \in I \setminus \{f\}}\right) dP \\ &\quad + \int_{X''} u_f^x \left(\sigma'_f(x), (\sigma_j(x))_{j \in I \setminus \{f\}}\right) dP. \end{aligned}$$

Since $\sigma'_f(x) = \sigma_f(x)$ for all $x \in X \setminus X''$ we have that

$$\int_{X \setminus X''} u_f^x \left(\sigma'_f(x), (\sigma_j(x))_{j \in I \setminus \{f\}}\right) dP = \int_{X \setminus X''} u_f^x \left((\sigma_j(x))_{j \in I}\right) dP.$$

Besides,

$$\begin{aligned}
& \int_{X''} u_f^x \left(\sigma_f'(x), (\sigma_j(x))_{j\in I\setminus\{f\}}\right) dP \\
= & \int_{X''} \left[(p_f - p)\sum_{i=1}^{n} n_j q - c \sum_{i\in N\setminus N^{x,YES}} d(b_i) - c \sum_{i\in N^{x,YES}} d(B_i^*)\right] dP \\
> & \int_{X''} \left[(p_f - p)\sum_{i=1}^{n} n_j q - c \sum_{i\in N\setminus N^{x,YES}} d(b_i) - c \sum_{i\in N^{x,YES}} d(B_i)\right] dP \\
= & \int_{X''} u_f^x \left((\sigma_j(x))_{j\in I}\right) dP.
\end{aligned}$$

Thus,

$$\begin{aligned}
u_f(\sigma\setminus\sigma_f') &> \int_{X\setminus X''} u_f^x \left((\sigma_j(x))_{j\in I}\right) dP + \int_{X''} u_f^x \left((\sigma_j(x))_{j\in I}\right) dP \\
&= \int_{X} u_f^x \left((\sigma_j(x))_{j\in I}\right) dP = u_f(\sigma),
\end{aligned}$$

which contradicts that σ is a BNE. ■

Statement 2. Let $\sigma = (\sigma_i)_{i\in I}$ be a BNE of $\left(I, (\Sigma_i)_{i\in I}, (u_i)_{i\in I}\right)$. For each $x \in X$ and each $i \in N$ such that $\int_{\pi_i(x)} dP > 0$ we have that

$$\int_{x'\in\pi_i(x)} u_i^{x'} \left((\sigma_i(x'))_{i\in I}\right) dP \geq p n_i q \int_{\pi_i(x)} dP.$$

Proof of Statement 2. Let $x \in X$ and $i \in N$ such that $\int_{\pi_i(x)} dP > 0$ and $\sigma_i(x) = NO$. Then, vessel i receives its initial FADs and hence

$$\int_{x'\in\pi_i(x)} u_i^{x'} \left((\sigma_i(x'))_{i\in I}\right) dP = \int_{x'\in\pi_i(x)} p n_i q dP = p n_i q \int_{\pi_i(x)} dP.$$

Let $x \in X$ and $i \in N$ such that $\int_{\pi_i(x)} dP > 0$ and $\sigma_i(x) = YES$. Suppose not. Then,

$$\int_{x'\in\pi_i(x)} u_i^{x'} \left((\sigma_i(x'))_{i\in I}\right) dP < p n_i q \int_{\pi_i(x)} dP.$$

Let σ_i' be such that $\sigma_i'(x') = NO$ when $x' \in \pi_i(x)$ and $\sigma_i'(x') = \sigma_i(x')$ otherwise. Now,

$$\begin{aligned}
u_i(\sigma\setminus\sigma_i') &= \sum_{X_i\in\pi_i} \int_{x'\in X_i} u_i^{x'} \left(\sigma_i'(x'), (\sigma_j(x'))_{j\in I\setminus\{i\}}\right) dP \\
&= \sum_{X_i\in\pi_i\setminus\pi_i(x)} \int_{x'\in X_i} u_i^{x'} \left(\sigma_i'(x'), (\sigma_j(x'))_{j\in I\setminus\{i\}}\right) dP \\
&\quad + \int_{x'\in\pi_i(x)} u_i^{x'} \left(\sigma_i'(x'), (\sigma_j(x'))_{j\in I\setminus\{i\}}\right) dP
\end{aligned}$$

Since $\sigma_i'(x') = \sigma_i(x')$ when $x' \in X_i \in \pi_i \backslash \pi_i(x)$ we have that

$$\sum_{X_i \in \pi_i \backslash \pi_i(x)} \int_{x' \in X_i} u_i^{x'} \left(\sigma_i'(x'), (\sigma_j(x'))_{j \in I \backslash \{i\}} \right) dP = \sum_{X_i \in \pi_i \backslash \pi_i(x)} \int_{x' \in X_i} u_i^{x'} \left((\sigma_j(x'))_{j \in I} \right) dP.$$

Since $u_i^x \left(\sigma_i'(x'), (\sigma_j(x'))_{j \in I \backslash \{i\}} \right) = pn_i q$ when $x' \in \pi_i(x)$ we have that

$$\begin{aligned} \int_{x' \in \pi_i(x)} u_i^{x'} \left(\sigma_i'(x'), (\sigma_j(x'))_{j \in I \backslash \{i\}} \right) dP &= pn_i q \int_{\pi_i(x)} dP \\ &> \int_{x' \in \pi_i(x)} u_i^{x'} \left((\sigma_i(x'))_{i \in I} \right) dP. \end{aligned}$$

Thus,

$$\begin{aligned} u_i(\sigma \backslash \sigma_i') &> \sum_{X_i \in \pi_i \backslash \pi_i(x)} \int_{x' \in X_i} u_i^{x'} \left((\sigma_j(x'))_{j \in I} \right) dP + \int_{x' \in \pi_i(x)} u_i^{x'} \left((\sigma_i(x'))_{i \in I} \right) dP \\ &= u_i(\sigma), \end{aligned}$$

which contradicts that σ is a BNE. ■

We now prove (b). We know that

$$u_i(\sigma) = \sum_{X_i \in \pi_i} \int_{X_i} u_i^x \left((\sigma_i(x))_{i \in I} \right) dP = \sum_{X_i \in \pi_i : \int_{X_i} dP > 0} \int_{X_i} u_i^x \left((\sigma_i(x))_{i \in I} \right) dP$$

By statement 2,

$$\sum_{X_i \in \pi_i : \int_{X_i} dP > 0} \int_{X_i} u_i^x \left((\sigma_i(x))_{i \in I} \right) dP \geq pn_i q \sum_{X_i \in \pi_i : \int_{X_i} dP > 0} \int_{X_i} dP.$$

Since P is a probability, $\int_X dP = 1$. Then,

$$pn_i q \sum_{X_i \in \pi_i : \int_{X_i} dP > 0} \int_{X_i} dP = pn_i q \int_X dP = pn_i q.$$

Besides,

$$\begin{aligned}
\sum_{i=1}^{n} u_i(\sigma) &= \sum_{i=1}^{n} \int_X u_i^x\left((\sigma_i(x))_{i\in I}\right) dP = \int_X \sum_{i=1}^{n} u_i^x\left((\sigma_i(x))_{i\in I}\right) dP \\
&= \int_X \left[\sum_{i\in N\setminus N^{x,YES}} pn_i q + \sum_{i\in N^{x,YES}} p\left|B_i\right| q\right] dP \\
&= pq \int_X \left[\sum_{i\in N\setminus N^{x,YES}} n_i + \sum_{i\in N^{x,YES}} n_i\right] dP \\
&= pq \int_X \left[\sum_{i\in N} n_i\right] dP = pq \sum_{i\in N} n_i \\
&= \sum_{i\in N} pn_i q.
\end{aligned}$$

Since $u_i(\sigma) \geq pn_i q$ for each $i \in N$ and $\sum_{i=1}^{n} u_i(\sigma) = \sum_{i\in N} pn_i q$ we deduce that $u_i(\sigma) = pn_i q$ for each $i \in N$.

Proposition 1 says nothing about the utility obtained by the firm. Thus, a natural question that arises is the following: is it possible to find BNE where some vessels share its FADs? Notice that if the answer is YES, then the firm can improve its utility by the fuel's savings.

Next examples show that the answer depends on P and the location of the FADs.

Example 1. Consider the case where we have two vessels ($I = \{f, a, b\}$) and each vessels has two FADs. Besides every vessel knows the location of every FAD. Namely, P assign probability 1 to element $x = \left(b_a^1, b_a^2, b_b^1, b_b^2\right)$ and zero to the rest of elements of X. The distances between the FADs and the vessels are the following:

distances	1	2	b_a^1	b_a^2	b_b^1
2	50				
b_a^1	5	45			
b_a^2	35	15	30		
b_b^1	15	35	10	20	
b_b^2	45	5	40	10	30

The distances are computed by assuming that vessels are located in a line. From left to right $1\,[5]\,b_a^1\,[10]\,b_b^1\,[20]\,b_a^2\,[10]\,b_b^2\,[5]\,2$. The distance between vessel 1 and FADs b_a^1 is 5; the distance between FADs b_a^1 and b_b^1 is 10 and so on.

Let σ be the BNE where each vessel says NO. Then, each vessels recover its FADs. Vessel a moves to FAD b_a^2 (distance 5), next to FAD b_a^2 (distance 30) and then back (35). The total distance traveled is 70. Similarly, the distance traveled by vessel b is also 70. Then, the utility of each vessel is $2pq$ and the utility of the firm is $(p_f - p)\,4q - c140$.

Let σ be such that each vessel says YES and the firm assign FADs b_a^1 and b_b^1 to vessel a and FADs b_a^2 and b_b^2 to vessel b. It is easy to see that σ is a BNE. Besides the utility of the firm is $(p_f - p)\,4q - c60$. Thus, in this BNE the firm can improve with respect to the initial situation.

Example 2. Consider the same case as in Example 1 but now the distances between the FADs and the vessels are the following:

distances	1	2	b_a^1	b_a^2	b_b^1
2	140				
b_a^1	5	135			
b_a^2	105	15	120		
b_b^1	125	35	100	20	
b_b^2	135	5	110	10	30

The distances are computed by assuming that vessels are located in a line. From left to right $1\,[5]\,b_a^1\,[100]\,b_b^1\,[20]\,b_a^2\,[10]\,b_b^2\,[5]\,2$.

In this example the unique BNE is the one where each vessel says NO. Notice that if both vessels say YES then the firm assign FAD b_a^1 to vessel a and the other FADs to vessel b. Thus, vessel a is better saying NO than saying YES.

A.2 Mechanism 2. Reassigning FADs with compensation

We now introduce the theoretical model for analyzing this case. The Aumann model of incomplete information $\left(I, X, (\pi_i)_{i\in I}, P\right)$ associated to this case is the same as above.

The non-cooperative game $\Gamma^x = \left(I, (A_i^x)_{i\in I}, (u_i^x)_{i\in I}\right)$ we consider is defined bas follows. $(A_i^x)_{i\in I}$ is the same as in Case 1. Nevertheless $(u_i^x)_{i\in I}$ will be modified in order to consider the compensation that firm give to vessels that share its FADs. Let $(a_i^x)_{i\in I} \in \times_{i\in I} A_i^x$.

Let $j \in N$ be a vessel that said NO (namely $a_j^x = NO$). Then, the vessel continue with the same FADs, b_i. Hence its utility is $u_j\left((a_i^x)_{i\in I}\right) = pn_jq$. This utility is the same as in Mechanism 1.

Let $j \in N$ be a vessel that said YES (namely $a_j^x = YES$). Then, the vessel has a new set of assigned FADs, B_j. Hence its utility is

$$u_j\left((a_i^x)_{i\in I}\right) = p\max\{|B_j|, n_j\}\,q$$

where $|B_j|$ denotes the number of FADs in B_j. Notice that if vessel j receives at least n_j FADs, then it will be paid according with the FADs received. If vessel j receives less than n_j, then it will be paid as if the vessel receives n_j FADs. In this part appears clearly the new incentive mechanism.

Finally, the utility of the firm $u_f\left((a_i^x)_{i\in I}\right)$ is given by

$$(p_f-p)\sum_{i=1}^{n} n_j q - c\sum_{i\in N\setminus N^{x,YES}} d(b_i) - c\sum_{i\in N^{x,YES}} d(B_i) - \sum_{i\in N^{x,YES},|B_i|<n_i} p(n_i-|B_i|)\,q$$

The utility of the firm has four parts. The first one, $(p_f-p)\sum\limits_{i=1}^{n} n_j q$, the second one, $-c\sum\limits_{i\in N\setminus N^{x,YES}} d(b_i)$, and the third one, $-c\sum\limits_{i\in N^{x,YES}} d(B_i)$, are the same as in the previous case. In this case it appears a fourth one,

$$-\sum_{i\in N^{x,YES},|B_i|<n_i} p(n_i-|B_i|)\,q,$$

where it appears the compensation that the firm gives to the vessels that say YES and receive less FADs than initially.

We now make a theoretical analysis of the Bayesian game $\left(I,(\Sigma_i)_{i\in I},(u_i)_{i\in I}\right)$ associated to this case.

Proposition 2. Let $\left(I,X,(\pi_i)_{i\in I},P\right)$ be the Aumann model of incomplete information defined as above.

(a) Let $\sigma^{NO}=\left(\sigma_i^{NO}\right)_{i\in I}$ be such that for each $i\in N$ and for each $x\in X$, $\sigma_i^{NO}(x)=NO$. Then, σ^{NO} is a BNE of $\left(I,(\Sigma_i)_{i\in I},(u_i)_{i\in I}\right)$ and for each $i\in N$, $u_i\left(\sigma^{NO}\right)=pn_iq$.

(b) Let $i\in N$ and $x\in X$. We define $a_i^{x,YES}=YES$ and $a_i^{x,NO}=NO$. For each $\left(a_j^x\right)_{j\in I}\in\times_{i\in I}A_i^x$ we have that

$$\int_{x'\in\pi_i(x)} u_i^{x'}\left(a_i^{x,YES},\left(a_j^x\right)_{j\in I\setminus\{i\}}\right)dP \geq \int_{x'\in\pi_i(x)} u_i^{x'}\left(a_i^{x,NO},\left(a_j^x\right)_{j\in I\setminus\{i\}}\right)dP.$$

(c) There exists a BNE $\sigma^{YES}=\left(\sigma_i^{YES}\right)_{i\in I}$ of $\left(I,(\Sigma_i)_{i\in I},(u_i)_{i\in I}\right)$ where for each $i\in N$ and for each $x\in X$, $\sigma_i^{YES}(x)=YES$. Besides, for each $i\in I$, $u_i\left(\sigma^{YES}\right)\geq u_i\left(\sigma^{NO}\right)$.

Proof of Proposition 2. (a) It is similar to the proof of Proposition 1 (a).

(b) We know that for each $x'\in\pi_i(x)$ and each $\left(a_j^x\right)_{j\in I}\in\times_{i\in I}A_i^x$

$$\begin{aligned} u_i^{x'}\left(a_i^{x,NO},\left(a_j^x\right)_{j\in I\setminus\{i\}}\right) &= pn_iq \text{ and}\\ u_i^{x'}\left(a_i^{x,YES},\left(a_j^x\right)_{j\in I\setminus\{i\}}\right) &= p\max\left\{n_i,\left|B_i^{x'}\right|\right\}q \end{aligned}$$

where $B_i^{x'}$ is the set of FADs assigned to vessel i after saying YES. Thus, the result holds trivially.

(c) For each $x \in X$ we take $\sigma_f^{YES}(x) = (B_i^*)_{i \in N^{x,YES}}$ where

$$c \sum_{i \in N^{x,YES}} d(B_i^*) + \sum_{i \in N^{x,YES}, |B_i| < n_i} p(n_i - |B_i^*|) q$$

$$= \min \left\{ c \sum_{i \in N^{x,YES}} d(B_i) + \sum_{i \in N^{x,YES}, |B_i| < n_i} p(n_i - |B_i|) q : (B_i)_{i \in N^{x,YES}} \in B^{x,YES} \right\}$$

We first prove that σ^{YES} is a BNE. We need to prove that for each $i \in I$ and each $\sigma_i \in \Sigma_i$ we have that $u_i(\sigma^{YES}) \geq u_i(\sigma^{YES} \backslash \sigma_i)$.

Because of the definition of σ_f^{YES} it is clear that for any $\sigma_f \in \Sigma_f$, $u_f(\sigma^{YES}) \geq u_f(\sigma^{YES} \backslash \sigma_f)$.

Let $i \in N$ and $\sigma_i \in \Sigma_i$. In the proof of Proposition 1 we have seen that

$$u_i(\sigma^{YES}) = \sum_{X_i \in \pi_i} \int_{X_i} u_i^x \left(\left(\sigma_i^{YES}(x) \right)_{i \in I} \right) dP.$$

Let $X_i \in \pi_i$ be such that $\sigma_i(x) = YES$ when $x \in X_i$. Then, $\sigma_i^{YES}(x) = \sigma_i(x)$ and hence,

$$\int_{X_i} u_i^x \left(\left(\sigma_i^{YES}(x) \right)_{i \in I} \right) dP = \int_{X_i} u_i^x \left(\sigma_i(x), \left(\sigma_i^{YES}(x) \right)_{i \in I \backslash \{i\}} \right) dP.$$

Let $X_i \in \pi_i$ be such that $\sigma_i(x) = NO$ when $x \in X_i$. By part (b),

$$\int_{X_i} u_i^x \left(\left(\sigma_i^{YES}(x) \right)_{i \in I} \right) dP \geq \int_{X_i} u_i^x \left(\sigma_i(x), \left(\sigma_i^{YES}(x) \right)_{i \in I \backslash \{i\}} \right) dP.$$

Thus,

$$u_i(\sigma^{YES}) \geq \sum_{X_i \in \pi_i} \int_{X_i} u_i^x \left(\sigma_i(x), \left(\sigma_i^{YES}(x) \right)_{i \in I \backslash \{i\}} \right) dP = u_i(\sigma^{YES} \backslash \sigma_i).$$

We now prove that for each $i \in I$, $u_i(\sigma^{YES}) \geq u_i(\sigma^{NO})$. Using part (b) it is straightforward to prove that for each $i \in N$, $u_i(\sigma^{YES}) \geq u_i(\sigma^{NO})$.

Since no vessel share its FADs in σ^{NO} we have that for each $x \in X$,

$$u_f^x(\sigma^{NO}) = (p_f - p) \sum_{i=1}^{n} n_j q - c \sum_{i \in N} d(b_i)$$

and hence

$$u_f(\sigma^{NO}) = \int_X u_f^x(\sigma^{NO}) dP = (p_f - p) \sum_{i=1}^{n} n_j q - c \sum_{i \in N} d(b_i).$$

We know that

$$u_f\left(\sigma^{YES}\right) = (p_f - p)\sum_{i=1}^{n} n_j q - c\sum_{i\in N} d\left(B_i^*\right) - \sum_{i\in N, |B_i|<n_i} p\left(n_i - |B_i^*|\right) q$$

where $\{B_i^*\}_{i=1}^n$ is obtained through the minimization problem defined above.

Thus, for proving that $u_f\left(\sigma^{YES}\right) \geq u_f\left(\sigma^{NO}\right)$ is enough to prove that it exists $\{B_i\}_{i=1}^n$ such that

$$c\sum_{i\in N} d\left(B_i\right) + \sum_{i\in N, |B_i|<n_i} p\left(n_i - |B_i|\right) q \leq c\sum_{i\in N} d\left(b_i\right).$$

If we take $B_i = b_i$ for all $i = 1, ..., n$ we realize that the previous inequality holds. ■

Next example shows that in some cases, the BNE of parts (a) and (c) could be, in a practical way, the same. Nevertheless our simulations based on real-data will show that both BNE could be very different.

Example 3. Consider the same case as in Example 1 but now the distances between the FADs and the vessels are the following:

distances	1	2	b_a^1	b_a^2	b_b^1
2	120				
b_a^1	5	115			
b_a^2	10	110	5		
b_b^1	110	10	105	100	
b_b^2	115	5	105	10	5

The distances are computed by assuming that vessels are located in a line. From left to right $1\,[5]\,b_1^1\,[15]\,b_1^2\,[100]\,b_2^1\,[5]\,b_2^2\,[5]\,2$.

In the BNE described in part (a) each vessels recover its FADs. Then, the utility of each vessel is $2pq$ and the utility of the firm is $(p_f - p)\,4q - c40$. In the BNE described in part (c) each vessels share its FADs. Then the firm reassign all FADs. But the optimal solution is to assign to each vessel its initial FADs. Then, every vessel recover its FADs. Hence, the utility of each vessel is $2pq$ and the utility of the firm is $(p_f - p)\,4q - c40$. Even from a theoretical point of view both equilibria are different, in a practical way, both are the same.