The University of Adelaide
School of Economics

Research Paper No. 2013-18
November 2013

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Stephanie McWhinnie and Kofi Otumawu-Apreku

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School of Economics, University of Adelaide

**Abstract**

Efficiency analysis in fisheries is not uncommon. In the past, efficiency analysis has mainly focused on productivity, cost and revenue, with relatively few investigating profit efficiency. Negative profits and small sample sizes in fisheries have been some of the obstacles diverting attention from this direction. We consider a new approach in the context of fisheries to overcome these challenges and examine profit efficiency in the rock lobster fisheries of South Australia. Specifically, we apply Nerlovian and Directional Distance Function methods to decompose profit efficiency of the rock lobster fishery into technical and allocative efficiencies. We use meta-frontier efficiency techniques to compare the Northern and Southern zone rock lobster fisheries. Results show that profit inefficiency in the South Australian rock lobster fishery can be largely attributed to allocative inefficiency. Results also show significant variability between efficiency levels in the Northern and Southern zones.

*We are extremely grateful to EconSearch, particularly Dr. Julian Morison and Dr. Adrian Linnane (SARDI) for making this firm level data available to us. We are also thankful to AARES 2013 (Sydney) conference participants for their valuable comments and feedback.

†Corresponding authors: Dr. Stephanie McWhinnie, Senior Lecturer, School of Economics, University of Adelaide. Email: stephanie.mcwhinnie@adelaide.edu.au. Kofi otumawu-Apreku, PhD Candidate. Email: kofi.otumawu-apreku@adelaide.edu.au

***JEL Classification:*** *Q2, Q22*
***Key words:*** *fisheries, profit efficiency, nerlovian, directional distance functions, meta-frontier anlysis, bootstrapping*

# 1 Introduction

The South Australian Rock Lobster Fishery comprises of the Northern and Southern Zone fisheries. The fishery is the most valuable in the state's commercial fishing industry. Between 1997/98 and 2008/09 the export value of rock lobster from the state was, on average, about $88 million per annum. In the 2008/09 fishing period, the fishery contributed nearly 41% of all fisheries' contribution to South Australia's gross state product (GSP). The rock lobster fishery's contributions to employment and household income in the state's fishery sector were 36% and 39%, respectively, in the 2008/09 period. Economic and biological sustainability of the fishery is, therefore, important to both managers and firms in the sector.

Issues confronting this valuable sector of the state's economy include falling biomass levels, as well as economic challenges. Between 1997/98 and 2009/10 fishing periods, the sector registered 26% and 67% declines in catch levels in the Southern and Northern Zones, respectively. The fall in catch is attributed to significant and persistent reductions in stock levels over the period. At the same time the average harvest cost has been on the increase in both fisheries. For example, cost per kilogram of harvest increased by about 97% in the Southern Zone, with harvest cost in the Northern Zone registering a 128% increase. These challenges have meant that profit in the fishery has seen significant fluctuations over the same period.[1] Differing cost structures in the two fisheries, in addition to higher revenues in the Southern fishery create the impression that the Southern Zone is more profitable and therefore

[1]All figures are summaries of figures obtained from EconSearch, 2011. The export value is free-on-board (fob) value. We are extremely grateful to EconSearch, particularly Dr. Julian Morison (Director, EconSearch), for making this firm level data available to us. EconSearch is a research body established in 1995 to provide economic research and consulting services in agricultural and resource industries throughout Australia (EconSearch, 2011). EconSearch collects the confidential data and provides reports to the state fisheries regulator, PIRSA.

more efficient. Even though the Southern Zone makes higher profits, compared to its northern counterpart, it is possibly the case that it is not achieving maximum profits given its cost structure and technology. Significant fluctuations in stock and profit levels, the importance of the fishery to the state's economy and, therefore, the need to understand the future of the fishery, show that there is compelling need for critical evaluation of the sector's economic performance.

This paper uses the Nerlovian and Directional Distance Function approach to analyze profit efficiency in the fishery. In the context of fisheries the application of the Nerlovian and Distance function methods is new. Advantages of this method are that it has decomposition power as well as the ability to handle negative profits. There are a number of studies done in the past on the South Australian Rock Lobster Fishery.[2] However, to our knowledge there are no studies of profit *efficiency* and hence none that have employed the Nerlovian and Directional Distance Function techniques.[3] The paper also tests if indeed the Southern fishery is more profit efficient compared to its Northern counterpart. The study includes four fishing years in the period 1997 to 2008, for which data is available. This period covers two management systems in the fishery: the total allowable commercial catch (TACC) and the individual transferable quota (ITQ) management systems. This makes it possible to compare the pre- and post-management changes and any possible effects on profit efficiencies. To compare the economic performance of the Northern and Southern fisheries, we make the necessary assumptions and carry out a meta-frontier analysis.

We show that though operational cost in the Southern Zone is lower than in the Northern Zone, on average the Northern Zone appears to be a little more profit efficient than the Southern Zone. The average total variable cost in the Northern Zone ranged between \$171,805 and \$247,108 for the 1997/98 to 2007/08 fishing pe-

[2] See (McGarvey et al., 1998; McGarvey and Matthews, 2001; Mulwa et al., 2009; EconSearch, 2011; Punt et al., 2012).

[3] Currently there are no studies analysing profit efficiency in the South Australian Rock Lobster Fishery. Existing investigations are analysis of annual profit levels in the fisheries; these investigations have consistently shown higher profit levels in the Southern Zone fishery (EconSearch).

riod. For the same period the average total variable cost in the Southern Zone was between \$124,583 and \$216,047. For the same period, however, profit efficiency (inefficiency) in the Northern Zone was between 59 - 78% (22 - 41%), on average, with the Southern Zone registering profit efficiency (inefficiency) levels of 53 - 77% (23 - 47%), on average.[4] This result further confirms evidence in the literature indicating that contrary to expectations a firm's cost efficiency may not necessarily explain its performance in terms of profit efficiency (Berger and Mester, 1997).

Efficiency analysis helps decision makers identify sources of inefficiency in their management units. Profit efficiency evaluation is a valuable exercise that helps to tease out inefficiencies that result from choosing suboptimal input-output mix. Technical challenges of measurement and decomposition of profit inefficiency have often overshadowed the relevance of profit efficiency analysis in fisheries. This difficulty, to a large extent, explains the relatively small number of empirical studies on profit efficiency even in the banking sector (Resende and Silva, 2007). In fisheries Fox et al. (2003), Dupont et al. (2005), and others use index number techniques to examine profit efficiency. In the past efficiency studies in fisheries have focused on productivity, technical, cost, and in some instances, revenue and profit analysis.[5] Attention to profit efficiency analysis has been minimal compared to cost. The presence of huge subsidies in fisheries, including state contributions the world over (Sumaila et al., 2010), may make even failing fishing firms appear efficient when the emphasis is placed on cost efficiency measures alone. Input subsidies may mask real input costs thereby reducing the full impact of input cost on maximum attainable profit.

Profit efficiency is found to account for errors on both the output and input sides. Evidence suggests that inefficiencies on output side may be as large or larger than inefficiencies on the input side (Berger et al., 1993). This has led to the assertion that the profit efficiency concept is superior to that of cost efficiency when evaluating

[4] In Subsection 6.2 we test whether these efficiency measures are significantly different, and show that they are indeed statistically different. See detailed analysis in Section 6.

[5] Details are discussed later in this Section.

overall firm performance. Further to that, it has been shown that while productivity gains may have the potential to contribute to increase in profit, changes in other factors such as changes in output and input prices can as well affect profitability.[6] The literature points out that the omission of the revenue side, under cost measurement, may introduce significant empirical distortions.[7] Inefficiencies resulting from suboptimal choice of input-output mix constitute a wider source of information and, therefore, presents a more accurate picture of efficiency levels in decision making units (Anderson et al., 2000). Furthermore, compared to cost, profit efficiency combines both cost and revenues in the analysis of technical and allocative efficiencies (Pasiouras et al., 2009). Currently the volume of studies on efficiency in fisheries is large but few (Fox et al. (2003), and Dupont et al. (2005), for example) specifically examine profit efficiency.

Nerlove (1965) is credited for the introduction of the profit efficiency notion. The Nerlovian idea is to decompose profit maximization by maximizing the profit of a given production function, and finding the maximum profit by maximizing overall production function (Färe and Grosskopf, 2000). The Nerlovian approach assumes firm price-taking behaviour and gives an indication of profit losses due to suboptimal choice of the input-output mix. Nerlove's application was in the context of parametric estimation of production functions. Nonetheless, Banker and Maindiratta (1988), and later Färe and Grosskopf (1995) have demonstrated that the non-parametric approach to profit efficiency computation can well rely on the established Nerlovian theoretical concepts. The Nerlovian measure has decomposition power in addition to being well defined for zero and negative profits.[8] It is, however, important to note that the Nerlovian measure is not without shortcomings. For instance, the measure requires inputs and outputs to be strictly positive. This requirement could be too

[6]See Berger and Mester (1997) on the superiority of the profit efficiency concept. For the effect of factor and output price changes on profitability see Kompas et al. (2009)

[7]Resende and Silva (2007) cite Maudos and Pastor (2003) to point out why the omission of revenue in cost analysis is a problem.

[8]The decomposition power is attributed to the Chambers et al. (1998a) formulation. This property, it is believed, accounts for its popularity in recent times (Cherchye et al., 2008).

restrictive and may pose significant challenges when dealing with multiple outputs in a multi-species fishery. In other words, when a species is not harvested in a particular period the method can become inefficient. Another major drawback of the Chambers et al. (1998b) formulation is the choice of normalization and its economic interpretation.[9] The disadvantages notwithstanding, the Nerlovian method presents a huge advantage over a number of other methods currently used in profit efficiency analysis.

Consensus on the most appropriate technique for profit efficiency is yet to be achieved despite several techniques proposed in the past (Resende and Silva, 2007). In fisheries the introduction of the index number profit decomposition (INPD) method has proved to be an important tool for analyzing firm performance. The decomposition of profit helps to distinguish the economic impact of management decisions from all other factors that influence profitability in fisheries. Parametric and non-parametric techniques have also been used to analyze efficiency measures in fisheries, including profitability.[10] Both methods provide valuable insights for researchers and managers in the industry. However, the stochastic frontier, a parametric method, has been found not to be flexible when it comes to profit decomposition (Fox et al., 2003). Despite its decomposition power the inability of the INPD method to overcome the negative profit problem remains a setback, particularly in fisheries where negative profits are not a rare phenomenon.[11]

[9]The choice of normalization and its economic interpretation challenges remain unresolved. For details see Nowlis and Van Benthem (1998).

[10]Studies employing these methods in fisheries include Kirkley et al., 2002; Fox et al., 2003; Dupont et al., 2005; Grafton et al., 2006; Costello and Deacon, 2007; Pascoe and Robinson, 2008; Kompas et al., 2009. For details on INPD in fisheries see Fox et al.(2003), Sharp et al. (2004), McWhinnie (2006).

[11]For example, Färe and Grosskopf (2000) show that the additive structure of the profit function makes the radial Shephard type distance functions less appropriate dual model of technology for profit efficiency analysis. With the Shephard type radial input or output distance function efficiency can only be improved by altering all factors in the same direction. The Directional Distance Function, on the other hand, allows factors to change in opposite directions (Färe and Grosskopf, 2000). In other words, the Directional Distance Function allows distances to the frontier to be measured by simultaneous output expansion and input contraction (Nahm and Vu, 2013). In addition recent theoretical developments have focused on directional distance function techniques, with empirical application of these methods gaining more prominence. For further details on theoretical and empirical discussions, see Chambers et al., 1996; Chambers et al., 1998; Färe et al., 2004; Portela and

The rest of the paper is organized as follows. Section 2 gives background details of the South Australian Rock Lobster Fishery. In Sections 3 and 4 the theoretical details of the Nerlovian, Directional Distance and meta-frontier methods employed in this paper are explained. Section 5 describes the data and how it was organized for use. In Section 6 the empirical application of the methods are fully explained and detailed analysis of the results are provided. Section 7 concludes that the Nerlovian method posseses computational advantage when it comes to negative profits, and gives future directions.

## 2 The South Australian Rock Lobster Fishery

The rock lobster fishery in South Australia is a state managed fishery. The fishery is the most valuable commercial fishery in the state. Being a state managed institution the fishery operates in accordance with management plans that fit into the primary management objectives (EconSearch, 2011). The fishery is separated into two zones; the Southern and Northern Zones. The separation of the fishery into the two zones was in recognition of the significant differences in both geological and ecological characteristics between the eastern and the western borders of the South Australian coasts where these fisheries are located. Whereas the geological and ecological structures of the Northern Zone afford less habitat for rock lobster species, the features in the Southern Zone, on the other hand, support higher densities of rock lobster (*Jasus edwardsii*). The Southern Zone with a coastline stretch of about 425km is more productive than its northern counterpart, which has a coastline stretch in excess of 3700km (PIRSA, 2012).[12] Both zones are further divided into regions, also known as marine fishing areas (MFAs). These MFAs demonstrate significant variations in catch and effort.

Thanassoulis, 2007.

[12]PIRSA: Primary Industries and Regions SA is the Government of South Australia's development agency responsible for research and policy development for the state's resources and industries.

The Northern Zone is divided into four regions, with the Southern Zone having three divisions. The large scale Northern Zone rock lobster (NZRL) fishery operates across an extensive coastline. The fishery stretches from the mouth of the Murray river to the Western Australian border in the Great Australian Bight and waters around the Kangaroo Island. The ecosystem supporting the Northern Zone rock lobster fishery is characterized by patchy reef formations with large expanse of sandy bottom. Environmental changes, coupled with the unique ecosystem characterization, results in unstable recruitment to the fishery (PIRSA, 2012). Vessels in the Northern Zone operate a one to ten days fishing per trip, with the Southern Zone operating a day fishery with vessels fishing close to their home port (PIRSA, 2012). Fishing cost is found to be higher in the Northern Zone than in the Southern Zone due to the relatively longer distances traveled in the Northern Zone (EconSearch, 2011).

The Southern Zone rock lobster (SZRL) fishery operates as a large scale fishery, extending across a long coastline, from the mouth of the Murray river to the Victorian border. Unlike the NZRL fishery, the habitat for the species in these waters is suitable for recruitment. The SZRL, like the Northern fishery, is a single species, single method fishery, based on the harvest of southern rock lobster (*Jasus edwardsii*). Compared to the NZRL, fishing costs in the SZRL fishery are generally lower (PIRSA, 2012). The short distance fishing day trip method of the SZRL largely explains the relatively lower fishing costs in this fishery. The geological, ecological, and environmental characteristics of the SZRL fishery provide suitable habitat for the fishery. These characteristics significantly contribute to high densities of the SZRL fishery. Figure 7, in Appendix (A.3), shows the boundaries of the Northern and Southern Zone fisheries with their respective regional or marine fishing areas.

In the period 1997 to 2011, available figures show significant fluctuations in harvest levels in the Northern Zone. These fluctuations are attributed to a number of factors including pot reductions and reductions in the number of fishing days in the fishery (EconSearch, 2011). Reductions in the total allowable commercial catch (TACC) since the introduction of quota management system in 2003/2004 fishing period, is also cited as a contributing factor to the fluctuations in harvest levels. Prior to 2003 only the Southern Zone rock lobster (SZRL) fishery operated under TACC management system. Quota management system was introduced in the Southern Zone in the 1993/94 period with subsequent TACC adjustments to account for falling biomass recruitment levels. However, it was not until 2003/04 when quota management system was introduced in the Northern Zone with TACC adjustments. Between 1997 and 2002 the Northern Zone was under various effort control management strategies. These strategies included flexible time closure, increase in size limit, and effort reduction. Since the introduction of the quota system, the main management strategy to ensure sustainability remains output control. Figure 1, below, shows changes in harvest and TACC levels over the period, 1997 to 2011. The TACC components of Figure 1 show the start of quota management systems in both fisheries. The quota system has full transferable rights. The fisheries are managed through output controls. The objective of this management strategy is to align harvest capacity with the biomass levels to ensure stock recovery and sustainability.

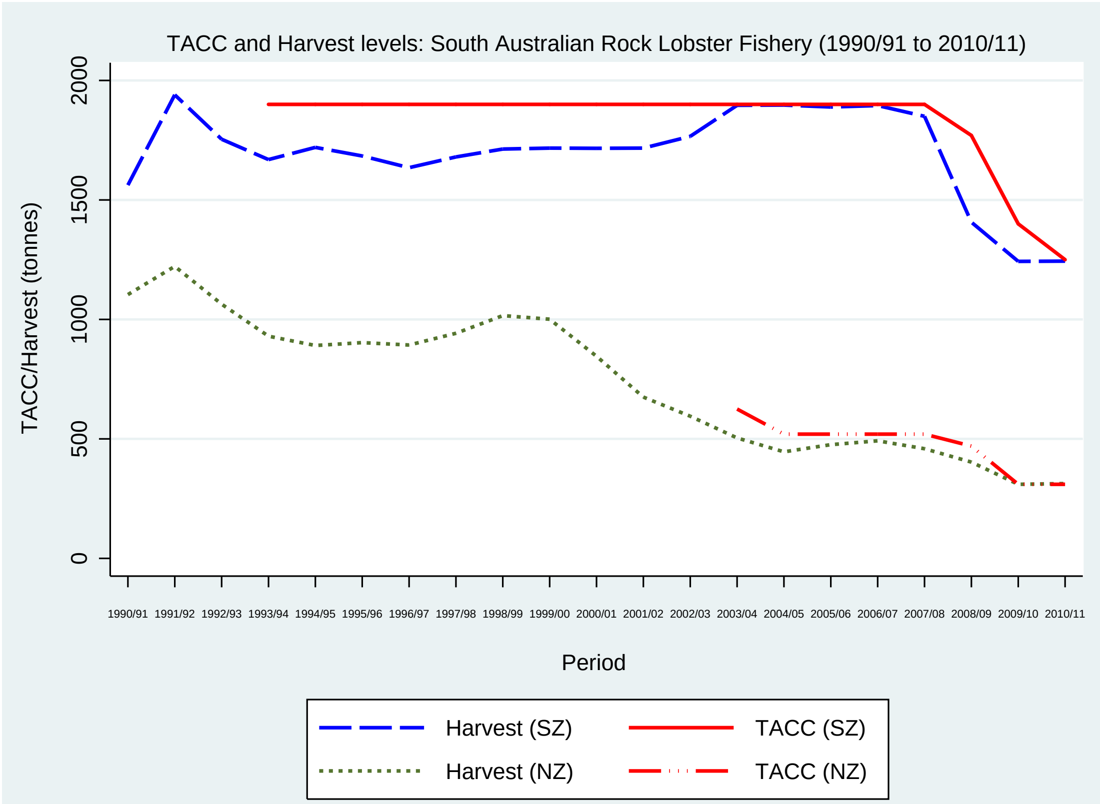


Figure 1: TACC and Harvest levels in the South Australian Rock Lobster Fishery between 1991 and 2011. Source: SARDI, 2012

From Figure 1,[13] it can be observed that whereas TACC and harvest levels in the Southern Zone remained fairly stable until 2002, the Northern Zone experienced persistent declines over the period. It is also observable that TACC levels in the Northern Zone, since the introduction of the quota system in 2003, were constantly adjusted downwards. In the case of the Southern Zone TACC levels remained constant until the 2007/2008 period when it started experiencing constant declines. The TACC adjustments strategy is a management plan aimed at ensuring stable maximum economic returns for the commercial fisheries. Fluctuations in catch levels coupled with exchange rate changes have meant that profits have not been stable over the pe-

[13]SARDI is the South Australian Government's principal research institute, a division of PIRSA (see SARDI, 2009; SARDI, 2012).

riod. Figures 2 and 3 show the fluctuations in both harvest and equity profit values between 1990 and 2008. Observe that the negative impact of fluctuations in catch seriously affect earnings in both Zones, with the Northern Zone suffering the greatest impact, particularly in the 2003/2004 fishing period.

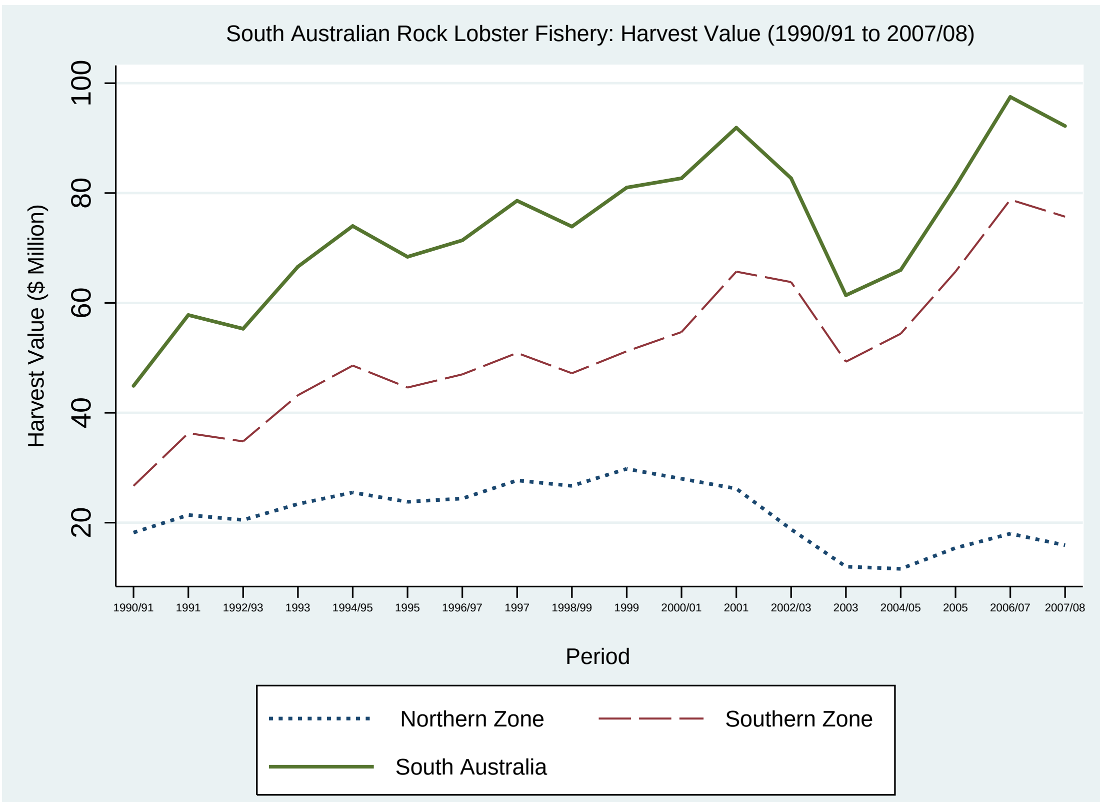


Figure 2: Harvest values of the South Australian Fishery: 1991 – 2008
Source: SARDI, 2009

Some of the precautionary management approach outlined in the 2007 - 2010 'Management Plan' of the Northern and Southern fisheries include; prior identification of undesirable outcomes and corresponding avoidance and corrective measures (PIRSA, 2012). Profit efficiency analysis fits well into this management frame. The decomposition of profit into technical and allocative efficiencies allows for the identification of challenges in the fishing and helps suggest corrective and avoidance measures.

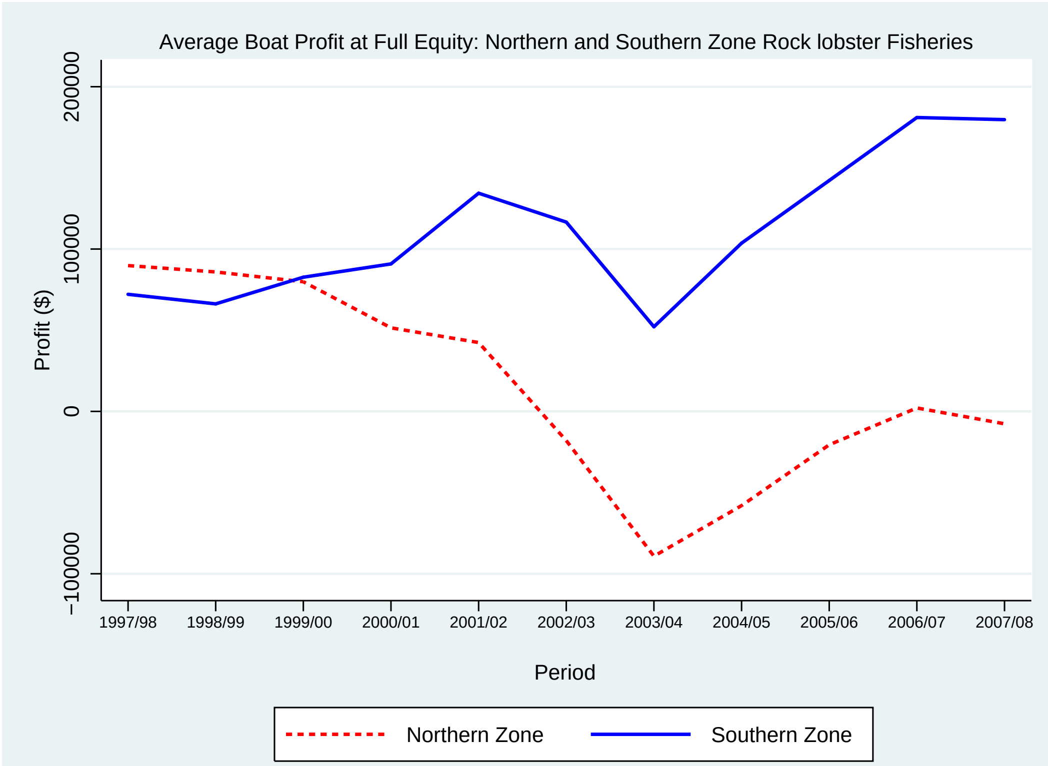


Figure 3: Boat Profit at Equity for Northern and Southern Zones: 1997 – 2008
Source: SARDI, 2009

# 3 Methods

This paper employs the Nerlovian profit efficiency and Directional Distance Function techniques to analyze profit efficiency of the South Australian Rock Lobster Fishery. We do this by first computing the profit efficiency measure, then decompose it into technical and allocative efficiency components. To obtain the profit efficiency measure the maximum attainable profit is first computed using the data envelopment technique.

Data envelopment analysis (DEA) is a linear programming technique proposed by

Charnes et al. (1978). The technique is used to determine the efficiency of a group of decision-making units relative to an efficient frontier (the envelope) by optimal input and output weights. A review of 196 studies assessing bank performance found that profit efficiency measures using DEA is rather limited (Fethi and Pasiouras, 2010). We focus on fishing firms' profit maximization and define the Nerlovian profit efficiency measure as introduced by Chambers et al. (1998b).

## 3.1 Nerlovian profit efficiency measure

Nerlove (1965) first proposed the ratio and the additive measures of profit efficiency. The ratio measure considered profit efficiency in proportionate terms, with the additive measure expressing efficiency due to profit loss in monetary terms (see Cherchye et al., 2008). Chambers et al. (1998b) propose a version of the Nerlovian measures that normalizes profits using input and output price vectors. This way the Nerlovian profit efficiency index is expressed as two components; the technical and allocative (Färe et al., 2008). The Chambers et al. (1998b) formulation is adopted in this paper. The Nerlovian profit efficiency measure (NE) for each firm $k$, is thus defined as:

$$NE\left(p,\ w,\ x^k,\ y^k;\ g_x, g_y\right) = \frac{\pi^*(p,\ w) - \pi^k(p,\ w)}{pg_y + wg_x}. \tag{1}$$

The Nerlovian measure is the normalized deviations between the maximum attainable profit and the firm's observed (actual) profit. In this expression $\pi^*(p,\ w)$ is the maximum attainable profit, and $\pi^k(p,\ w)$ the observed profit of firm $k$. The vectors $p = (p_1, . . ., p_M) \in \Re^N_+$ and $w = (w_1, . . ., w_N) \in \Re^M_+$ are, respectively, the output and input price vectors. The vectors $g_x \in \Re^N_+$ and $g_y \in \Re^M_+$ are the directional vectors normalizing the profits. The direction $(pg_y + wg_x)$ is the value of the normalization. It must be noted that the Nerlovian measure assumes price-taking behaviour and gives an indication of profit losses due to sub-optimal choice of the input-output mix.

The above definition of the Nerlovian measure implies that zero and negative profits pose no computational problems. In other words, it is well defined for zero and negative profits. This formulation also means that a fishing firm $k$, is fully profit efficient if and only if it achieves maximum profit, i.e. $\pi^k(p,\ w) = \pi^*(p,\ w)$. This implies that *NE* is equal to zero when a firm is fully efficient. Profit inefficiency is identified whenever *NE* is greater than zero. In other words, the level of a firm's efficiency (inefficiency) is higher (lower) the closer its *NE* measure is to zero. Taking $k = 1, . . ., K$ fishing firms as the decision-making units, given technology $T$, it is supposed that each firm $k$ chooses strictly positive input and output vectors; $x = (x_1, . . ., x_n) \in \Re_+^N$ and $y = (y_1, . . , y_m) \in \Re_+^M$, respectively, to maximize profit. The production technology, $T$, is specified as:

$$T = \left\{(x_k,\ y_k) :\ input\ x_k \in \Re_+^N\ \ can\ produce\ y_m \in \Re_+^M\right\}.$$

Thus $T$ is of the vector space $\Re_+^{M\,x\,N}$ $\left(i.e.,\ T \in \Re_+^{M\,x\,N}\right)$. We follow the literature and make the following standard assumptions in this paper: 1. the technology set, $T$, is closed; 2. free disposability of inputs and outputs; it is possible to waste inputs, that is, for $(x,\ y) \in T$, $x^{'} \geq x$, and $y^{'} \leq y$, imply $(x^{'},\ y^{'}) \in T$; 3. it is feasible to do nothing, that is, $(0,\ 0) \in T$ ; and 4. the technology, $T$, is convex. Though theoretically if $(x,\ y) \in T$, and $x = 0$, then $y = 0$, that is, no output is produced if there are no inputs, this paper implicitly assumes that firm $k$ chooses strictly positive input and output vectors. In practice the assumption is that a fishing firm chooses positive outputs to maximize profits.

Suppose the $k^{th}$ fishing firm faces input price vector $w = (w_1, . . ., w_n)$ together with output price vector $p = (p_1, . . ., p_m)$, then the profit efficiencies can be estimated. Expressing the firm's total revenue as:

$$py = \sum_{m=1}^{M} p_m y_m;\ m = 1, . . ., M$$

and associated total cost as:

$$wx = \sum_{n=1}^{N} w_n x_n; \;\; n = 1, . . ., N,$$

the firm's profit is then obtained as:

$$py - wx = \sum_{m=1}^{M} p_m y_m - \sum_{n=1}^{N} w_n x_n.$$

Firms seek to maximize this profit given the production technology set $T$. The maximized profit can be expressed as:

$$\begin{aligned} \pi^*(p,\ w) &= Max\,\{py - wx :\ (x,\ y) \in T\} \\ &= py^* - wx^*, \end{aligned}$$

with $(x^*,\ y^*)$ being the optimal input and output vectors that yield maximum profit at the given input and output price vectors $(w,\ p)$.[14] Solving the following linear programming (LP) problem, the maximum profit for the $k^{th}$ fishing firm relative to the technology, can be computed.

The LP for firm $k'$s maximum attainable profit is specified as:

$$\pi^{*k}(p,\ w) \;\; = \underset{x,\ y}{Max} \sum_{m=1}^{M} p^k_m y^{*k}_m - \sum_{n=1}^{N} w^k_n x^{*k}_n \tag{2}$$

[14]The profit function $\pi^*(p,\ w)$, satisfies all the usual assumptions of convexity and continuity, homogeneity and non-negative, non-increasing in $w$ and non-decreasing in $p$. For details, see Färe and Grosskopf (2005).

subject to

$$\begin{aligned}
\sum_{k=1}^{K} z^k y_m^k &\geq y_m^{*k}, \qquad m = 1, \ldots, M \\
\sum_{k=1}^{K} z^k x_n^k &\leq x_n^{*k}, \qquad n = 1, \ldots, N \\
\sum_{k=1}^{K} z^k &= 1, \qquad z^k \geq 0, \quad k = 1, \ldots, K
\end{aligned}$$

Thus given the technology, the $k^{th}$ fishing firm chooses inputs $(x_n)$ and outputs $(y_m)$ to maximize profits. Following the literature the intensity variables, $z^k$, are restricted to unity, that is, $\sum_{k=1}^{K} z^k = 1$. The convexity constraint in the above DEA (LP) program is given by $\sum z^k = 1$, imposing a variable return to scale (VRS) technology. This ensures that an efficient fishing firm is compared to a fishing firm of similar size. Further, the imposition of VRS condition in the maximum profit model, introduced earlier in this Section, implies that perfect competition is not assumed. This also means that maximum profit may be different from zero (Koutsomanoli-Filippaki et al., 2012). This is perfectly legitimate in our application since we consider fishing firms under the individual transferable quota (ITQ) management system, different from the perfect competition open access case. Having established the profit efficiency measure the next step is to decompose it into technical and allocative components. The decomposition is done using the directional distance function.

## 3.2 Directional distance function

The technical component of the Nerlovian measure is defined by the directional distance function. The directional distance function measures the distance from an input-output vector within a feasible technology frontier along a chosen directional vector. Färe and Grosskopf (2000) define the directional distance function (DDF) by assuming convexity and closedness of the production technology as conditions ensuring the duality between the DDF and the profit function. Following these assumptions we state the DDF on the technology as:

$$\overrightarrow{D_T}(x,\ y;\ -g_x,\ g_y) \ = \ sup\left\{\beta :\ (x-\beta g_x,\ \ y+\beta g_y)\in T\right\}.$$

It is important to note that the DDF differs from the traditional Shephard type distance functions in a number of ways (Färe and Grosskopf, 2000). One major difference is the requirement that the DDF be associated with an explicit direction in which efficiency is measured. The specified directional vector, $g = (-g_x,\ g_y)$, is the vector earlier defined. The DDF seeks for the greatest possible input contraction in the negative direction $(-g_x)$ in order to obtain the maximum attainable expansion of outputs in the positive direction $(g_y)$. Chambers et al. (1998b) and Färe and Grosskopf (2005) prove that this is true if and only if $(x,\ y) \in T$. By the simultaneous input contraction and output expansion feature the DDF represents the technical inefficiency of an input-output vector achieving maximal profit (Nahm and Vu, 2013).

Before a graphical illustration of the function is given it is important to explain the frontier concept. The frontier determines maximal output capacity of decision-making units given input levels. The frontier is determined using DEA to establish the maximum potential output for a given set of inputs, and it is primarily used to estimate efficiency. The frontier can be described as an efficient envelopment surface, enveloping the production of a set of decision-making units under a specified technology. With the variable returns to scale (VRS) assumption, points lying on the frontier define the envelope and are efficient, while points lying below the frontier are not efficient. The envelopment surface and the efficient projection path to the surface are the key constructs of the DEA model (Cherchye et al., 2008). The projection path is determined by the model's orientation, that is, whether it is input or output orientation.

For capacity estimation purposes in fisheries output orientation has generally been estimated empirically (Pascoe et al., 2003). In this paper, input orientation estimation is employed given the objective to examine efficient utilization of inputs to maximize profits. The maximum profit line which is also established by solving the linear programing function specified in Section 3.1 above depicts the maximum attainable profit that a firm can obtain given input and output market price levels. A decision-making unit is profit efficient if its output level is on the frontier and is tangent to the maximum profit line. A simple illustration of the function is shown in Figure 4 below.

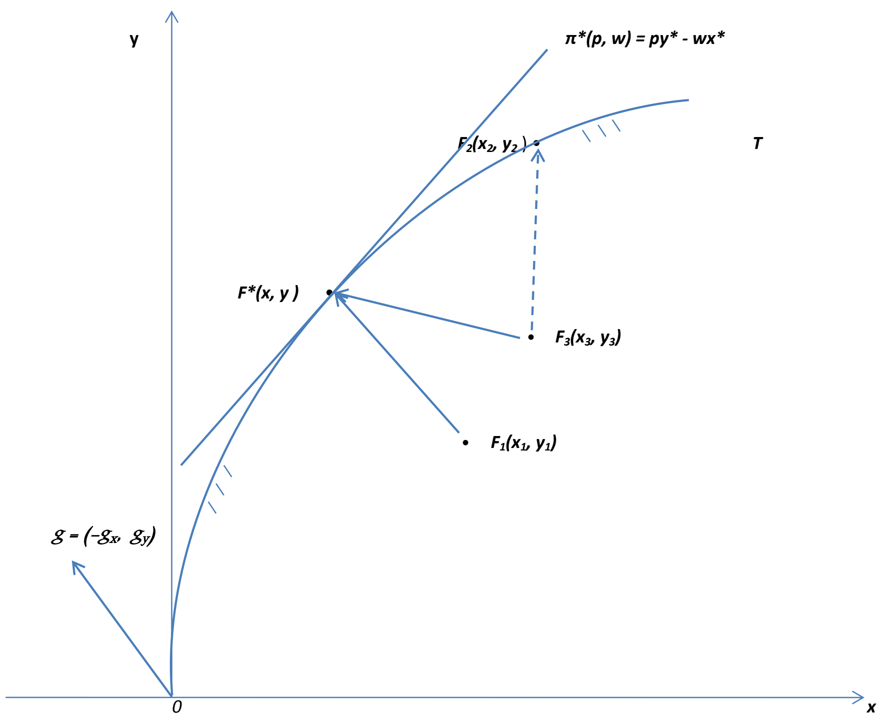


Figure 4: A simple illustration of the Directional Distance Function

Figure 4, gives a simple one-input, one-output illustration of DDF. It shows the direction, $g = (-g_x,\ g_y)$, in which firms $F_1$ and $F_3$ must contract the input, given technology $T$, in order to expand output and attain the maximum attainable and efficient profit of firm $F^*$. Firm $F^*$, being on that part of the frontier where it is tangent to the maximum attainable profit, $\pi^*(p, w)$, is fully efficient, both technically and allocatively. Firm $F_2$ on the other hand, lies on the frontier so is technically efficient, but it is not tangent to maximum profit so is not allocatively efficient and, therefore, not optimal for firm $F_3$ to try to achieve the level of efficiency associated with $F_2$.

Next we illustrate the DEA estimation of the distance function. Including all inputs and outputs as the constraint set, the distance function for the $k^{th}$ fishing firm is estimated as:

$$\overrightarrow{D_T}(x^k,\ y^k;\ -g_x,\ g_y) \quad = \quad \underset{\beta,\ z}{Max}\ \beta \tag{3}$$

subject to

$$\begin{aligned}
\sum_{k=1}^{K} z^k y_m^k &\geq y_m^{k^*} \beta g_y, \quad m = 1, \ldots, M \\
\sum_{k=1}^{K} z^k y_m^k &\leq x_n^{k*} - \beta g_x, \quad n = 1, \ldots, N \\
\sum_{k=1}^{K} z^k &= 1, \ z^k \geq 0, \qquad k = 1, \ldots K,
\end{aligned}$$

where $z^k$ are the intensity variables and $\beta$ a parameter representing the magnitude by which input must be contracted and outputs expanded (Färe and Grosskopf, 2000). Here again the convexity constraint is given by $\sum z^k = 1$, imposing a VRS technology. The convexity constraint also ensures that efficient firms are only benchmarked against their peers, that is, firms of similar sizes are compared (Coelli et al., 2005). It must be noted that the differences in the envelopment surface is determined by the underlying assumptions of the DEA model. In general the constant returns to scale (CRS) and VRS assumptions are used. The VRS embodies both increasing and decreasing returns to scale. That is to say, the VRS frontier reflects the possibility of production technology exhibiting increasing, constant, and decreasing returns to scale.[15] In this paper the VRS is employed with the implicit assumption that the fishery is subject to VRS, with a long-run objective in mind.

In order to establish the dual relationship between the profit function and the DDF the translated vector is proved to be feasible (Färe and Grosskopf, 2000). This means that the translated vectors of the inputs and outputs belong to the technology set. The translated vector is expressed as:

$$\left(x - \overrightarrow{D_T}(x,\ y;\ \ -g_x,\ g_y)g_x,\ y + \overrightarrow{D_T}(x,\ y;\ \ -g_x,\ g_y)g_y\right) \in T$$

For input and output price vectors, $w = (w_1, . . ., w_n) \in \Re_+^N$, and $p = (p_1, . . ., p_m) \in \Re_+^M$, respectively, the profit function is defined as $\pi^*(p,\ w) \geq py - wx$, for all $(x,\ y) \in T$. This implies that the efficient profit is no less than the value of the feasible input-output vector. Thus, given the feasibility of the translated vector, profit function for the $k^{th}$ fishing firm can be expressed as:

$$\begin{aligned} \pi^{*k}(p,\ w) &\geq p\left(y^k + \overrightarrow{D_T}(x^k,\ y^k;\ \ -g_x,\ g_y)g_y\right) - w\left(x^k - \overrightarrow{D_T}(x^k,\ y^k;\ \ -g_x,\ g_y)g_x\right) \\ &\geq (py^k - wx^k) + \overrightarrow{D_T}(x^k,\ y^k;\ \ -g_x,\ g_y)(pg_y + wg_x). \end{aligned}$$

This function establishes the relationship between firm $k's$ profit function $\pi^{*k}(p,\ w)$ and the DDF, $\overrightarrow{D_T}(x,\ y;\ \ -g_x,\ g_y)$. This relation can also be interpreted to mean that the firm's maximal profit is greater than or at least equal to the actual or observed profit, plus the gain in profit resulting from reductions in technical inefficiency. The firm's maximal profit, given the translated vector, can be re-arranged to establish the duality between the price dual and the quantity primal in a general form as:

$$\pi^*(p,\ w) \ = \underset{(x,\ y)\geq 0}{Max} \ \left\{py - wx + \overrightarrow{D_T}(x,\ y;\ \ -g_x,\ g_y)(pg_y + wg_x)\right\}.$$

[15]For more details on DEA estimations and returns to scale assumptions, see Coelli, et al. (2005).

From this the DDF is recovered as:

$$\overrightarrow{D_T}(x,\ y;\ \ -g_x,\ g_y)\ \ = \underset{(x,\ y)\geq 0}{Max}\ \left\{\frac{\pi^*(p,\ w)-(py-wx)}{pg_y+wg_x}\right\}.$$

From the firm's specific profit function established earlier it can be observed, after the necessary re-arrangement, that a firm's profit efficiency in general can be expressed as:

$$\frac{\pi^*(p,\ w)-(py-wx)}{pg_y+wg_x}\ \ \geq\ \ \overrightarrow{D_T}(x,\ y;\ \ -g_x,\ g_y).$$

The above inequality is explained by the possible presence of inefficient allocation of resources even when all technical inefficiencies are eliminated (Fukuyama and Weber, 2004). For example, in Figure 4 it is observed that though firm $F_2$ is technically efficient for being on the efficient frontier, it is not profit efficient. The presence of inefficient resource allocation in firm $F_2$ is a possible source of its profit inefficiency.[16] The inequality is thus closed when the allocative inefficiency component is added, resulting in equality of the above expression. This means that the allocative inefficiency is residually determined from the Nerlovian profit and technical (DDF) inefficiencies. It should be observed that the elimination of technical and allocative inefficiencies is expected, all else remaining constant, to achieve full efficiency. The equality between the profit, technical, and allocative efficiencies is given by the following expression:

$$\frac{\pi^*(p,\ w)-(py-wx)}{pg_y+wg_x}\ \ =\ \ \overrightarrow{D_T}(x,\ y;\ \ -g_x,\ g_y)+AE. \tag{4}$$

The left hand side, the price dual, of this equation is thus the normalized deviations between the firm's maximum attainable profit and the observed (actual) profit in the Nerlovian efficiency measure. The right hand side, the quantity primal, is the technical and allocative efficiencies (Färe et al., 1997; Chambers et al., 1998).[17] This

[16] The presence of other possible sources of inefficiency is explored in our second paper that follows this.

[17] By technical efficiency it is meant by how much a DMU is able to increase outputs and decrease

gives the full decomposition of the $NE$ into technical (DDF) and allocative efficiency ($AE$) measures. In practice the directional vectors are set to the value of the observations. This means $g_x = x$, and $g_y = y$.

We have set up the methodology with which we estimate profit efficiency. That is, first details of the Nerlovian measure were discussed, then the DDF was introduced and explained. We will use these measures to compute profit efficiency for the South Australian Rock Lobster Fishery in Section 6, but first we introduce the concept of a meta-frontier as a way in which we analyze the profit efficiency estimates.

# 4 Meta-Frontier Analysis

This Section introduces the meta-frontier concept. The Section further shows how the concept is applied to accommodate the possibility that variations in natural endowment and technological differences across firms may lead to biased efficiency estimates when only regional frontiers, other than a 'global' frontier, are considered. In Section 2, the geological, ecological and environmental differences between the two fisheries, Northern and Southern, were clearly outlined. We apply the meta-frontier concept to these fisheries to investigate differences in efficiency measures, if any, between the two fisheries.

The meta-frontier concept, proposed by Hayami and Ruttan (1971), was defined as the envelope of commonly conceived classical production function (Mulwa and Emrouznejad, 2011). Meta-frontier was later considered as some form of global frontier, capturing regional (zonal) specific characteristics in an enveloping frontier to make efficiency comparisons across regions more meaningful (Battese et al., 2004). In this

inputs in order to maximize profit. Allocative efficiency, on the other hand, reflects the additional profit attainable through optimal choices in the input-output mix. In the fisheries under consideration since output is controlled through a firm's quota, allocative efficiency may primarily result from effort/input choices within a firm's quota to take advantage of input-output prices in any given fishing season.

sense the efficiency of a production unit is assessed with reference to its own region (zone) frontier, but the production environment facing the region is assessed through the distance between the regional (zonal) frontier and the meta-frontier (O'Donnell et al., 2010). In the efficiency literature the meta-frontier model was introduced to accommodate the possibility that regional variations in natural endowment and technological differences across firms may lead to biased estimates of efficiency scores (Assaf and Matawie, 2010; Zibaei, 2012). It has been demonstrated that the use of traditional production models to compare the efficiency of firms with diverse environmental backgrounds is not appropriate (O'Donnell et al., 2008). Meta-frontier analysis is shown to consider possible variations across firms in efficiency investigations. The application of frontier models in the assessment of efficiency levels in fisheries remains popular, however, meta-frontier models in the fisheries economics literature are not common (Zibaei, 2012).

Efficiency analysis is often based on the assumption that all production units are similar, operating under similar production technology and, therefore, these units can be evaluated under a single frontier (O'Donnell et al., 2010). On the other hand, evidence shows that production units in a given sample may operate in slightly different production environments giving rise to different production possibility sets. Differences in social, physical, and economic characteristics may be reflected in the heterogeneity of production technologies across firms (O'Donnell et al., 2008). Given such environmental heterogeneity production units may make choices from different production possibility sets. In such situations, estimating efficiency under a single frontier will yield efficiency estimates that do not accurately measure the capacity of the production units (O'Donnell et al., 2010). Comparing efficiency levels of decision-making units (DMUs) across regions with different environmental, ecological and other characteristics, the frontier for the regions must be the same (O'Donnell et al., 2008). The meta-frontier approach allows for evaluation and comparison of the efficiency of production units having access to different production possibility sets (Battese et al., 2004). Currently the meta-frontier approach is common in efficiency analysis in finance and banking (O'Donnell and Westhuizen, 2002; O'Donnell et al., 2008; Kontolaimou and Tsekouras, 2010), education (McMillan and Chan, 2006), agriculture (Hayami and Ruttan (1971); Mulwa et al., 2009), the tourism and hospitality industry (Mulwa and Emrouznejad, 2011), but few in fisheries (Zibaei, 2012).

The Northern and Southern Zone rock lobster fisheries of South Australia possess distinctive differences in their geological, ecological, and environmental characteristics, as earlier outlined. Ignoring the distinct features of these fisheries in any efficiency comparison of the two may lead to biased efficiency scores and therefore result in misleading policy implications (Battese et al., 2004). We use the meta-frontier model to analyze and compare the Nerlovian profit efficiency measures of the Northern and Southern Zone rock lobster fisheries of South Australia.

As mentioned elsewhere in this paper parametric and non-parametric methods are usually employed in efficiency investigations, including meta-frontier efficiency analysis. The non-parametric data envelopment analysis (DEA) method is used in this study. The DEA technique has been discussed earlier. In the Section that follows the meta-frontier is introduced and details of the meta-frontier technology explained.

## 4.1 Meta-frontier framework

This Section outlines the theoretical framework of the meta-frontier method. The set up considers $V > 1$ fishing zones, the Northern and Southern fisheries, with each region having $k = 1, 2, ..., K$ decision-making units, the fishing firms. Specifically, for each $v-$region we assume there exits $v_k$ firms such that $v_k \in V_K$, where $V_K$ is the set of all firms in all zones. Fishing firms in each zone, $v$, are also assumed to operate under region specific technology, $T^v$.

### 4.1.1 The frontiers

The following theoretical formulation largely follows Rao et al. (2003) and Battese et al. (2004). For strictly positive input vectors $x \in \Re_+^N$, the set of all inputs which can produce a defined set of positive output vector $y$ (i.e., $y \in \Re_+^M$), given a production technology set $T$, can be expressed as: $X(y) = \{x : (x, y) \in T\}$. The boundaries of this set define the 'isoquants' (Rao et al., 2003). The set of all output vectors that any input vector, $x$, can produce given the production technology $T$, can also be defined as: $Y(x) = \{y : (x, y) \in T\}$. The boundary of the output set defines the production possibility frontier which represents the technically efficient production. Battese et al. (2004) then describe the meta-frontier as a production function 'enveloping' separate regional (in this case, zonal) production technology sets with each having its own defined environmental factors.

The above formulation means that for positive input and output vectors $x \in \Re_+^N$ and $y \in \Re_+^M$, respectively, the production possibility set, technology, of each zone $v$, can be defined as:

$$T^v = \left\{(x, y) : x \in \Re_+^N, \textit{ can produce } y \in \Re_+^M\right\}.$$

Given $T^v$, the meta-frontier technology set is defined (Battese et al., 2004) as:

$$\begin{aligned} T^* \;=\; & \left\{(x, y) : x \in \Re_+^N, \textit{ can produce } y \in \Re_+^M \right. \\ & \left. \textit{in at least one zonal technology}, T^1, T^2, \ldots.., T^V\right\} \end{aligned}$$

This means that a given input-output combination $(x, y)$, in any given zone, $v$, is part of the meta-frontier technology, $T^*$. In each zone $v$ technology, $T^v$, all the production axioms, including weak disposability, closedness and boundedness, and convexity, are assumed. Rao et al. (2003) show that if the regional (zonal) technologies defining the meta-frontier technology satisfy all the production axioms then $T^*$ also satisfies these axioms except the convexity axiom. To ensure that the meta-frontier technology satisfies the convexity axiom, $T^*$ is defined as the convex monotone hull of the region specific technologies (Rao et al., 2003) and expressed as:

$$T^* \equiv Convex\ monotone\ hull\ \left\{T^1 \cup T^2 \cup \ldots \cup T^V\right\}.$$

The meta-frontier is then constructed by pooling all observation units from each region (zone) (Battese et al., 2004). Detailed description of the frontier concept is given in Section 3.2 above. Figure 5 below is an illustration of the meta-frontier construction. In Figure 5, the meta-frontier envelopes all the three regional frontiers. Like the frontiers earlier discussed in Section 3.2, the variable returns to scale (VRS) assumption implies that points lying on the meta-frontier define the envelope and are technically efficient, while points lying below the frontier, in this case the regional frontiers below it, are not efficient. The closeness of each regional frontier to the meta-frontier is defined by the distance of each regional frontier from the meta-frontier. This means in Figure 5, the frontier of region 2 is closest to the meta-frontier and therefore firms in this region are, on average, more efficient compared to firms in regions 3 and 1, whose frontiers lie below that of region 2. Region 1 being the farthest from the meta-frontier means that firms in region 1 are, on average, least efficient compared to firms in regions 2 and 3.

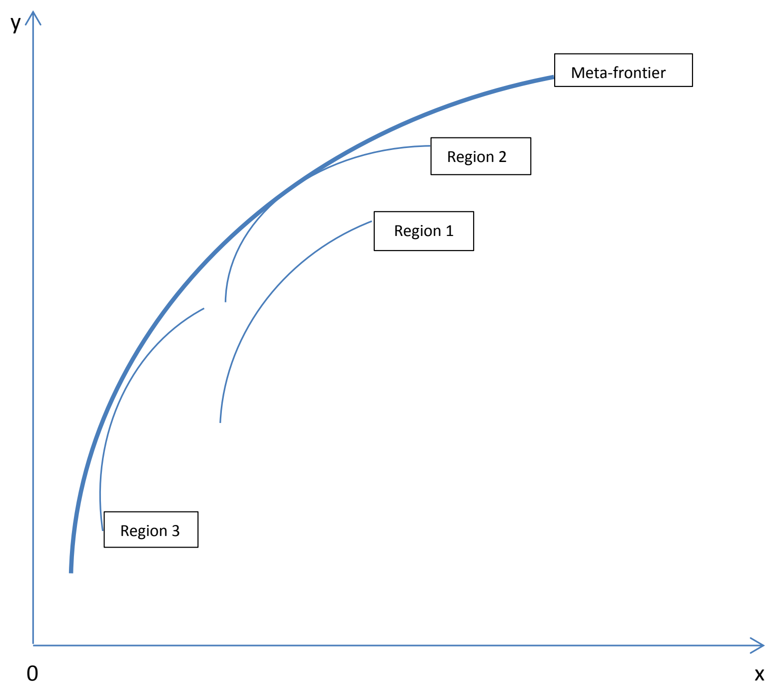


Figure 5: A graphical illustration of meta-frontier and regional (zonal) frontiers.

#### 4.1.2 Profit efficiency under meta-frontier

Profit efficiency can be considered as a measure of the distance between a given profit generated by an input-output combination and an optimal point on a profit frontier. From the meta-frontier technology concept it is feasible to identify regional profit efficiency frontiers, applying DEA to the data on the decision-making units from the zones (regions) (Mulwa and Emrouznejad, 2011). We follow Mulwa and Emrouznejad and use the DEA method discussed earlier in this paper to construct $L$ zonal (regional) frontiers, one for each zone (region), $v$, with data on each fishing firm $k$ (i.e., data on $k = 1, 2, ...., K$). The VRS assumption is used here to specify the LP for the frontier, for same reasons earlier discussed.

The LP for the maximum profit of the $k^{th}$ fishing firm, in region $v$ is expressed as:

$$\pi^{*vk}(p,\, w) = \underset{x,\, y}{Max} \ \sum_{m=1}^{M} p_m^{vk} y_m^{*vk} - \sum_{n=1}^{N} w_n^{vk} x_n^{*vk} \tag{5}$$

subject to

$$\begin{aligned} \sum_{k=1}^{K} z^{vk} y_m^{vk} &\geq y_m^{*vk}, & m &= 1, . . ., M \\ \sum_{k=1}^{K} z^{vk} x_n^{vk} &\geq x_n^{*vk}, & n &= 1, . . ., N \\ \sum_{k=1}^{K} z^{vk} &= 1, \quad z^{vk} \geq 0, & k &= 1, . . ., K \end{aligned}$$

Notice that the above maximum profit function is a simple transformation of the profit function introduced in Section 3. The vector $y_m^{vk}$ is the $(K \times M)$ output quantities for the $k^{th}$ fishing firm in Zone $v$; $x_n^{vk}$ is the $(K \times N)$ input quantity vector for the $k^{th}$ fishing firm in zone $v$; and $z^{vk}$, the vector of weights. The maximum profit for the $k^{th}$ firm in zone $v$, given respective output and input price vectors, $p$ and $w$, is denoted as $\pi^{*vk}(p,\, w)$. The LP is solved $K$ times, once for each region, $v$, and producing optimal input-output vectors $(x_n^{*vk},\, y_m^{*vk})$ which give maximum profit, and $z^{vk}$ vectors.

Construction of the meta-frontier, as explained earlier, is by pooling observations of all decision-making units from all zones (regions). This means the $K$ fishing firms in all the zones will give a number of frontiers from the pooled data. Representing the total number of frontiers generated by $L\,(l = 1, 2, ..., L)$, the resulting LP model for the $k^{th}$ firm in zone $v$, consisting of the input-output matrices of the pooled data, is expressed (Mulwa and Emrouznejad, 2011) as:

$$\pi^{*lk}(p,\, w) = \underset{x,\, y}{Max} \;\; \sum_{m=1}^{M} p_m^{lk} y_m^{*lk} \; - \sum_{n=1}^{N} w_n^{lk} x_n^{*lk} \tag{6}$$

subject to

$$\begin{aligned}
\sum_{k=1}^{K}\sum_{l=1}^{L} z^{lk} y_m^{lk} &\geq y_m^{*lk}, \qquad m = 1, \ldots, M \\
\sum_{k=1}^{K}\sum_{l=1}^{L} z^{lk} x_n^{lk} &\geq x_n^{*lk}, \qquad n = 1, \ldots, N \\
\sum_{k=1}^{K}\sum_{l=1}^{L} z^{lk} &= 1, \quad z \geq 0, \qquad l = 1, \ldots, L \\
& \qquad and \quad k = 1, \ldots, K
\end{aligned}$$

$\pi^{*lk}(p,\, w)$ is maximum profit in the meta-frontier, given price vectors $(p, w)$. The matrix of output quantities of the $k^{th}$ firm in the meta-frontier is given by $y_m^{lk}$. Similarly, in the meta-frontier are: $x_n^{lk}$, the matrix of unit $k'$s input quantities; and $z^{lk}$, the vector of weights. The input and output vector values $(x_n^{*lk},\; y_m^{*lk})$, give the maximum profits obtained from the meta-frontier.

### 4.1.3 The Directional distance function under meta-frontier

Like the profit efficiency under meta-frontier discussed above, the technical inefficiency (DDF) for the zonal (regional) frontiers is similarly obtained by simple transformation of the DDF function introduced in Section 3.2, and expressed as:

$$\vec{D}_T^{\,vk}(x^{vk},\, y^{vk};\;\; g_x,\, -g_y).$$

In addition, running the LP for the transformed version of the DDF produces the technical inefficiency for the $k^{th}$ firm in region $v$. A similar transformation of the zonal (regional) technical inefficiency estimates computed by the DEA program for the meta-frontier is expressed as:

$$\vec{D}_T^{\,lk}(x^{lk},\, y^{lk};\;\, g_x,\, -g_y). \tag{7}$$

It is noted that the maximum profit, $\pi^{*vk}(p,\, w)$, of any $k^{th}$ unit in a given zone, $v$, is no larger than the meta-frontier profit, $\pi^{*lk}(p,\, w)$. This results from the fact that the constraints in the regional LP are a subset of the constraints imposed on the meta-frontier LP problem (Mulwa and Emrouznejad, 2011). Likewise, the zonal frontier of the technical inefficiency estimates, $\vec{D}_T^{\,vk}(x^{vk},\, y^{vk};\;\, g_x,\, -g_y)$, are also no larger than the meta-frontier technical inefficiency estimates, $\vec{D}_T^{\,lk}(x^{lk},\, y^{lk};\;\, g_x,\, -g_y)$. Analogically, the decomposed Nerlovian profit efficiency estimates for the zonal and the meta-frontiers are respectively expressed as:

$$\frac{\pi^{*vk}(p,\, w) - (py^{vk} - wx^{vk})}{pg_y + wg_x} = \vec{D}_T^{\,vk}(x^{vk},\, y^{vk};\;\, g_x,\, -g_y) + \overrightarrow{AE}_T^{\,vk} \tag{8}$$

and

$$\frac{\pi^{*lk}(p,\, w) - (py^{lk} - wx^{lk})}{pg_y + wg_x} = \vec{D}_T^{\,lk}(x^{lk},\, y^{lk};\;\, g_x,\, -g_y) + \overrightarrow{AE}_T^{\,lk}, \tag{9}$$

where; $\overrightarrow{AE}_T^{\,vk}$ and $\overrightarrow{AE}_T^{\,lk}$, are the zonal and meta-frontiers of the allocative inefficiencies, respectively.

Now that we have definition of profit efficiency and its decomposition into technical and allocative components and the ability to compare across regions using meta-frontier, we can turn to the particular fishery question. To do this we first give detailed description of the data used in the next Section.

## 5 Data Description

Data on the South Australian Northern and Southern Zone rock lobster fisheries were obtained from EconSearch.[18] EconSearch collects confidential survey data from fishing operators in the Northern and Southern Zone fisheries for the estimation of various economic indicators.[19] The data are cross-sectional, covering the fishing periods 1997/98, 2000/01, 2004/05, and 2007/08. The surveys are voluntary, and due to legal reasons no identifiers are used. It is therefore not possible to track individual vessels over time. For each of these time periods the data are grouped separately into Northern (NZ) and Southern (SZ) zones. The data is grouped into four categories: boat variable costs, other variable costs, quasi-fixed, and fixed costs. Boat variable costs are catch level dependent and include: fuel, oil and grease, bait, ice, provisions, crew payments, fishing equipment (nets, pots, lines, etc), repairs and maintenance (sliping, painting, overhaul motor).

Other variable costs include owner-operated and unpaid family labor. The family labor cost is imputed based on amount of time and equivalent wage rates. Fixed and quasi-fixed costs, measured in current dollar values, include insurance, license and industry fees, office and business administrative costs, interest on loan repayment and overdraft, depreciation and leasing. The data also include boat catches, individual boat quotas, average beach price, as well as unit input costs. Tables 1 and 2, respectively, provide summary statistics of the discretionary variable and fixed inputs of the Northern and the Southern Zone fisheries, before grouping into the four categories mentioned above. The Tables show cost distributions across firms in both fisheries, with both fixed and variable costs, on average, being higher in the

[18]EconSearch is a research body established in 1995 to provide economic research and consulting services in agricultural and resource industries throughout Australia. (EconSearch Pty Ltd, November, 2011). EconSearch collects the confidential data and provides reports to the state fisheries regulator, PIRSA. We are extremely grateful to EconSearch, particularly Dr. Julian Morison, for making this firm level data available to us.

[19]According to EconSearch, though fishers in the rock lobster fishery may hold other licenses, data collected on rock lobster are strictly in relation to rock lobster licenses only. This means costs and profits can be solely attributed to rock lobster fishing activities.

Northern Zone than in the Southern Zone.

Table 1: Summary Statistics of discretionary variable inputs: Northern and Southern Zones (1997–2008)

| | Northern Zone | | | | Southern Zone | | | |
|---|---|---|---|---|---|---|---|---|
| | Statistics | | | | Statistics | | | |
| Variable inputs | 1997-98 | 2000-01 | 2004-05 | 2007-08 | 1997-98 | 2000-01 | 2004-05 | 2007-08 |
| Fuel | 25302 | 46473 | 45445 | 42855 | 15486 | 15502 | 18161 | 39453 |
| | *(14095)* | *(21733)* | *(21761)* | *(17261)* | *(10068)* | *(9517)* | *(10999)* | *(25429)* |
| | [2385, 60000] | [13636, 93636] | [16000, 83380] | [14280, 70000] | [3000, 43086] | [2727, 36364] | [3000, 65000] | [8500, 155000] |
| Repairs & Maintenance | 24816.28 | 30069 | 17466 | 23574 | 18415 | 12299 | 16624 | 26867 |
| | *(15251)* | *(17092)* | *(12358)* | *(9877)* | *(21214)* | *(8670)* | *(11743)* | *(22335)* |
| | [3300, 51627] | [7727, 71818] | [4000, 62700] | [3500, 43600] | [3200, 113000] | [2545, 45066] | [1200, 63000] | [2700, 119036] |
| Bait/Ice | 14161 | 16666 | 16750 | 13963 | 9482 | 7954 | 8906 | 18767 |
| | *(5015)* | *(3460)* | *(7649)* | *(4979)* | *(3945)* | *(3041)* | *(3710)* | *(8801)* |
| | [1537, 21000] | [9091, 23818] | [1000, 30000] | [5000, 22000] | [0.00, 17342] | [2273, 17569] | [0.00, 25116] | [7500, 45000] |
| Provisions | 7337 | 4566 | 4609 | 11421 | 3617 | 285 | 299 | 695 |
| | *(4895)* | *(2763)* | *(3610)* | *(9999)* | *(2590)* | *(520)* | *(1140)* | *(2182)* |
| | [100, 16000] | [0.00, 10000] | [0.00, 15800] | [1980, 48600] | [0.00, 9000] | [0.00, 2273] | [0.00, 10000] | [0.00, 15600] |
| Labor paid | 93550 | 128122 | 63406 | 70301 | 79973 | 83531 | 59044 | 107488 |
| | *(50480)* | *(48527)* | *(32450)* | *(39721)* | *(37130)* | *(55561)* | *(39201)* | *(59842)* |
| | [0.00, 190977] | [25000, 237000] | [20000, 142100] | [15000, 170000] | [19000, 149250] | [12000, 205000] | [0.00, 165000] | [25000, 349295] |
| Labor unpaid | 27209 | 17905 | 19077 | 21357 | 23433 | 17822 | 20862 | 22085 |
| | *(15962)* | *(12702)* | *(17976)* | *(13652)* | *(14628)* | *(18652)* | *(19302)* | *(10697)* |
| | [0.00, 62966] | [0.00, 46579] | [0.00, 66238] | [0.00, 42938] | [3490, 63808] | [0.00, 96520] | [0.00, 111976] | [6271, 69873] |
| Other variable inputs | 1856 | 3309 | 5051 | 976 | 2408 | 4472 | 688 | 693 |
| | *(3997)* | *(4997)* | *(8722)* | *(1045)* | *(4254)* | *(13594)* | *(1112)* | *(823)* |
| | [0.00, 12952] | [0.00, 18636] | [0.00, 39500] | [0.00, 4500] | [0.00, 16000] | [0.00, 68630] | [0.00, 7329] | [0.00, 4000] |
| Total variable cost | 194232 | 247108 | 171805 | 184447 | 152814 | 141864 | 124583 | 216047 |
| | *(50938)* | *(66142)* | *(56982)* | *(55111)* | *(50938)* | *(58993)* | *(43288)* | *(79823)* |
| | [49870, 305806] | [94868, 375044] | [88150, 358503] | [84980, 281948] | [62977, 313990] | [37998, 264382] | [32756, 240518] | [96187, 480308] |
| No. of Observations: | 18 | 24 | 22 | 19 | 26 | 26 | 82 | 55 |

*NB: Figures in each column are the means, standard deviations, minimum and maximum values. The first figures are the means, with the standard deviations in parentheses. Figures in square brackets are respectively, minimum and maximum values. All Figures are in Australian Dollars.*

*Data source: EconSearch.*

Table 2: Summary Statistics of discretionary quasi-fixed and fixed inputs: Northern and Southern Zones (1997–2008)

| | Northern Zone | | | | Southern Zone | | | |
|---|---|---|---|---|---|---|---|---|
| | Statistics | | | | Statistics | | | |
| Quasi-fixed/fixed inputs | 1997 – 98 | 2000 – 01 | 2004 – 05 | 2007 – 08 | 1997 – 98 | 2000 – 01 | 2004 – 05 | 2007 – 08 |
| License Fee | 13881 | 11906 | 19382 | 20752 | 13152 | 12427 | 15762 | 19316 |
| | *(1782)* | *(1455)* | *(5748)* | *(5427)* | *(2019)* | *(3244)* | *(4497)* | *(5244)* |
| | [10000, 18000] | [9091, 15455] | [15000, 37800] | [12000, 35000] | [9403, 16500] | [0.00, 16115] | [1000, 38894] | [10000, 36000] |
| Insurance | 8040 | 14939 | 8439 | 7427 | 4459 | 4071 | 6176 | 6492 |
| | *(2733)* | *(2923)* | *(3144)* | *(2677)* | *(2581)* | *(2064)* | *(2723)* | *(3413)* |
| | [5100, 14300] | [4545, 8717] | [2872, 16000] | [3000, 12698] | [0.00, 15500] | [1545, 9091] | [0.00, 13500] | [0.00, 22572] |
| Interest | 22135 | 35464 | 31500 | 42709 | 9274 | 17239 | 17683 | 26090 |
| | *(23629)* | *(37205)* | *(41287)* | *(49973)* | *(14211)* | *(14941)* | *(22953)* | *(32828)* |
| | [0.00, 100000] | [0.00, 163020] | [0.00, 150000] | [0.00, 182250] | [0.00, 50000] | [0.00, 60000] | [0.00, 111400] | [0.00, 120000] |
| Lab our unpaid | 10178 | 8850 | 13065 | 8486 | 4771 | 4778 | 7084 | 7500 |
| | *(5971)* | *(6278)* | *(123101)* | *(5425)* | *(2978)* | *(5001)* | *(6554)* | *(3633)* |
| | [0.00, 23554] | [0.00, 23021] | [o.00, 45362] | [0.00, 17062] | [711, 12992] | [0.00, 25880] | [0.00, 38025] | [2129, 23727] |
| Other fixed inputs | 62313 | 74696 | 79483 | 76739 | 36956 | 56437 | 58276 | 63173 |
| | *(17613)* | *(30769)* | *(46988)* | *(36657)* | *(16958)* | *(28465)* | *(27763)* | *(31851)* |
| | [27905, 88407] | [33637, 164814] | [23074, 240333] | [21475, 170533] | [15610, 104023] | [14756, 140291] | [18304, 160840] | [17391, 157566] |
| Total Fixed cost | 116547 | 139633 | 151868 | 156113 | 68612 | 94953 | 104982 | 122570 |
| | *(38245)* | *(45385)* | *(62748)* | *(52445)* | *(29670)* | *(32411)* | *(44284)* | *(58603)* |
| | [55935, 202994] | [63091, 244640] | [51130, 307873] | [62811, 261985] | [36827, 176734] | [32359, 179619] | [32904, 291466] | [41887, 312734] |
| No. of Observations: | 18 | 26 | 22 | 19 | 26 | 26 | 82 | 55 |

*NB: Figures in each column are the means, standard deviations, minimum and maximum values. The first figures are the means, with the standard deviations in parentheses. Figures in square brackets are respectively, minimum and maximum values. All Figures are in Australian Dollars.*

*Data source: EconSearch.*

In standard DEA applications when inputs are treated as choice variables the implicit assumption is that firms can vary all inputs to achieve efficiency. This corresponds to a long run analysis (Das and Ghosh, 2009). For analytical purposes we make this implicit assumption and treat all inputs as variable. We select the inputs believed to adequately describe the operations of the fisheries, and clean out outliers from the data. These data are used in the computation of the profit, directional distance, and allocative efficiency scores. Only the selected discretionary inputs are used.[20] However, differences such as boat engine capacity, engine age, boat size or length, as well as zone specific characteristics may all contribute to heterogeneity among

[20]Discretionary inputs are those inputs whose quantities can be varied by the fisher at will, and do not necessarily take into account environmental or non-discretionary inputs (Alfonso and Aubyn, 2008)

various firms even within the same fishery (i.e., the South Australian rock lobster fishery), and therefore influence firms' profit efficiency.[21]

We investigate two versions of the frontier analysis; the zone (region) specific frontier, and the meta-frontier. In the zone specific frontier we analyze firm performance in each zone separately. We do this on the assumption that firms within each separate zone are homogeneous. In order to compare firm performance across zones we carry out the meta-frontier analysis. The underlying assumption in the meta-frontier case is that zone characteristics are different across different zones, making firms heterogeneous when grouped together, that is, when grouped as one fishery.

The data also capture estimated biomass levels, boat length, boat age, engine age, and electronic equipment age. Average values of these non-discretionary variables are provided in Table 6 in Appendix A.[22] The 1997/98 period average values for the Northern Zone are generally lower compared to those of its Southern counterpart. A similar picture is observed for the 2000/01 period, except for electronic equipment age where the Northern Zone average is higher. The 2004/05 averages, on the other hand, show Northern Zone with much higher averages for boat age and electronic age. Northern Zone averages are, however, only higher in boat age and lower in all others, for the 2007/08 period. These variables are assumed to be accounting for regional differences and, therefore, used as non-discretionary variables in the truncation regression analysis that follows this paper.

In the Section that follows we give full description of the data organization for the computation of the zonal and meta-frontier efficiency measures. The Section first describes the data organization, then the computational process of the Nerlovian profit efficiency, the technical and allocative efficiencies for both the zonal and meta-frontiers. We then analyze the results of the zonal efficiency measures, compare the

[21] This is investigated in our next paper.

[22] We are most grateful to Dr. Adrian Linnaeus of PIRSA-SARDI, for making the biomass data available to us.

meta-frontier measures, and discuss the results.

# 6 Empirical Application and Analysis

Non-parametric profit efficiency evaluation starts with the computation of maximum attainable profit using DEA. We compute the maximum attainable profit of each firm and subtract from it the corresponding observed profits. Using the procedure described in Section 3, this yields the Nerlovian profit efficiency score (NE) for each firm. This is done for firms in both the Northern and Southern Zone fisheries for each fishing period, separately. Following the description of the DDF procedure in Section 3, we compute the DDF for each firm in each fishery separately, for each fishing period. The difference between the NE and the DDF scores then gives the AE scores as earlier described. The NE, as well as the DDF and, therefore, the AE, are bounded between 0 and 1. It must be emphasized that the Nerlovian and the technical measures are inefficiency measures, and so also are the allocative measures. This means that the closer the score is to 0 the lesser the level of inefficiency (or the higher the efficiency). In other words, a firm is more efficient the closer its measure is to 0, and less efficient the closer the measure is to 1. Following the theoretical framework in Section 4, we also pool the data for the two zones for each period and compute the meta-frontiers for the four periods. This is done using similar procedures described for the estimation of the individual zone efficiency estimates mentioned above. In the next Section these procedures are detailed.

## 6.1 Application

To compute the Nerlovian efficiency scores we organize the data in the following way. We first identify firm level input and output vectors. Output in this case is firms' fish catch or harvest, measured in tonnes. Firm level input and output price vectors are also specified. Inputs were grouped into four categories as earlier mentioned; boat variable inputs, other variable inputs, quasi-fixed, and fixed inputs. We include quasi-fixed and fixed inputs in order to measure efficiency at full equity. We use profit at full equity with the objective of analyzing the firms' efficiency in medium and long term horizon. Besides, profit at full equity is also considered a more useful absolute measure of economic performance of fishing firms (EconSearch, 2011). These inputs were aggregated using common denominators considered appropriate for each input type. For example, for inputs that are denominated by days fished, number of days fished is used as a common denominator for the aggregation. In other words, variables considered directly related to either days at sea, or harvest, were grouped accordingly.

Objectives of the aggregation are two fold. First, to reduce the number of variables used in the DEA function. This was to help minimize the dimensionality problem as much as possible, given the small number of observations, particularly in the case of the Northern Zone. The second objective was to help gauge out input prices. Input prices were not available and since the costs were dollar denominated, one way of obtaining unit prices was using the denominators as explained. For each fishery/zone we obtain input and output price vectors. These are one output vector, and a corresponding price vector, and four input vectors, together with their corresponding price vectors.

The Nerlovian efficiency measure is computed by first estimating the maximum profits. We do this using the maximum profit DEA function specified in Equation (2), Section 3.1. In this paper we use the **profit.max** program in Frontier Efficiency Analysis package with **R**, also known as FEAR.[23] Loading the organized data into this program we obtain the optimal outputs and inputs for the frontier for each Zone, that is, in the case of the Zone specific frontiers. In the case of the meta-frontier the optimal output and input are obtained for the meta-frontier, based on Equation (6). These optimal outputs and inputs, given prices, are then used to compute the optimal profit for each firm. The sensitivity of the DEA program requires that outliers are cleaned out of the data. The optimal profits are the maximum profits firms

[23]For details on this program, see Wilson (2010)

could achieve given the same input outlays. The fisheries in each zone can achieve these maximum profits if they are able to increase output levels to the optimal levels, compared to their actual observed output levels.

To estimate the Nerlovian measure in Equation (1), the denominator of this equation must be specified using the directional vector, $g = (g_y - g_x)$. The literature indicates that if firms technology are such that the maximum profit function produces same optimal inputs and outputs for all the firms in the group, then the direction to choose is $g = (y^*, x^*)$, where $y^*$, $x^*$ are, respectively, optimal outputs and inputs. In cases where the optimal inputs and outputs vary across firms or are not the same for each firm, the direction to choose could be $g = (1, -1)$ or $g = (\overline{y}, \overline{x})$. In this case $\overline{y}$, $\overline{x}$, are mean output-input vectors (Fukuyama and Weber, 2004). In this paper the direction $g = (y^*, x^*)$ is chosen in periods where the optimal inputs and outputs are not the same across firms and $g = (\overline{y}, \overline{x})$, where otherwise. This means that the denominator for the Nerlovian equation, Equation (1), is either $(py^* + px^*)$ or $(p\overline{y} + w\overline{x})$. For either option the price vectors, $(p, w)$, are multiplied by their corresponding outputs and inputs and summed. The Nerlovian measure for the meta-frontier is estimated by first using the **profit.max** program to estimate Equation (6).

It was earlier mentioned that some methods, for example the index methods, computationally do not allow negative profit firms to be examined in profitability analysis. Such firms are excluded from observations before any computation is done. The Nerlovian method, on the other hand, computationally makes it possible for such firms to be included in the observations and examined. However, we observe in this paper, that firms making excess losses end up with a Nerlovian measure greater than 1, because the numerator exceeds the denominator in Equation (1), in such cases. Given that a measure of 1 indicates complete inefficiency (i.e., 100% inefficient) any measure exceeding 1 does not yield any meaningful economic interpretation. For this reason such firms are excluded from further analysis. We drop about 7% of the observations (i.e., 6 observations out of 89 from the Northern Zone and nearly 5% (i.e., 9 out of 189) from the Southern Zone. On the other hand, we note that in fisheries and in other resource industries, where negative profit is not rare the NE may not be solving the negative profit problem entirely. Nevertheless, it is important to consider the ability to include all firms in the initial stage and be able to compute their profit efficiency as good and, therefore, an advantage of the Nerlovian method. The ability to compute the profit efficiency of each firm, whether or not the firm is making negative profits, offers some necessary information about individual firm performance. It offers managers of such firms the opportunity to appreciate the seriousness of the challenges they face and adopt necessary strategies to address them.

The technical (DDF) efficiency measure is estimated using the **ddf** program contained in the **nonparaeff** package in FEAR. For the estimation of this measure, the DDF specified in Equation (3), a directional vector must be chosen. The choice of the vector is informed by the optimal outputs and inputs resulting from the maximum profit function. For varying optimal output and inputs, either of two directions, $g = (1, -1)$ and $g = (\overline{y}, \overline{x})$ are used. The direction $g = (y^*, x^*)$ is recommended if optimal outputs and inputs are the same for all firms. Details were earlier discussed under the Nerlovian measure. The allocative inefficiency is then residually determined from Equation (4). The meta-frontier version of the DDF, Equation (7), is estimated using the **ddf** program. The meta-frontier allocative inefficiency is then established using the decomposition provided by Equation (9).

The DEA applications used in this paper, particularly the directional distance function, have been known to be sensitive to small sample sizes and number of variables used, known in the literature as the dimensionality problem. Given the sample sizes used in this paper it is important to employ statistical measures that will help draw accurate statistical inference. To do this we use the non-parametric bootstrap technique to bootstrap the efficiency estimates. The bootstrapping is done at this stage for a number of reasons. The bootstrap technique is useful in empirical applications when the theoretical distributions of the population is unknown. Using this non-parametric technique does not require any assumptions about the distribution of the population. It is also useful for making meaningful statistical inference when dealing with small sample sizes. Our sample sizes are small in many cases, particularly the Northern Zone (mostly less than 30 observations), so by re-sampling the estimates with re-placement we are able to draw reasonable statistical inference about the estimates in the population.

Using the bootstrap we draw different random samples from the observations in each zone by re-sampling with replacement. We use 5000 replications in each case. The method produces a distribution of the efficiency means, together with statistical properties such as standard errors, estimated biases, and bias corrected accelerated intervals (BCas) that make it possible to make the necessary statistical inferences. From the BCas the limits within which the unknown population efficiency means lie are identified, with some degree of confidence. We choose 95% confidence level in this case. The BCa is used to ensure extra accuracy. In Section 6.2 the results of the estimations are provided and analyzed.

## 6.2 Results and analysis

The inefficiency estimates are provided here in three parts: the zonal periods (i.e., zonal frontiers for each period); the period-by-period meta-frontier (i.e., the meta-frontier estimates for separate periods); and zonal periods and period meta-frontiers. In each part mean, minimum, and maximum estimates, estimated bias, and bias corrected accelerated intervals are provided. First, we analyze the zonal period frontier inefficiency estimates and then compare with the corresponding overall period meta-frontier estimates. We then do a comparative analysis of the zones for each period, by comparing their period-by-period meta-frontier estimates. We also provide evidence to show that the meta-frontier mean estimates for the two zones are statistically different. To do this we hypothesize that the distributions of mean inefficiency measures in the two zones are equal, and use the Welch two sample t-test to test the hypothesis. We find this necessary because in absolute terms the means of the meta-frontier estimates for the two zones appear to be close. Table 3 shows results for the Northern and Southern Zones, together with the corresponding overall meta-frontier estimates.

Table 3: Efficiency Estimates (Periods and Period-by-period meta-frontiers) : Northern and Southern Zones

| | | Zonal Frontier Estimates (Periods) | | | Meta-frontier Estimates (Overall) (Period-by-Period) | | |
|---|---|---|---|---|---|---|---|
| Zone<br>Period<br>(Obs: Zone/meta-frontier) | Statistics | Nerlovian Profit In eff. | Technical In eff. | Allocative In eff. | Nerlovian Profit In eff. | Technical In eff. | Allocative In eff. |
| Northern | Mean | 0.2005 | 0.0606 | 0.1399 | 22130 | 0.1073 | 0.1140 |
| 1997/98 | Min/Max | [0.0, 0.4267] | [0.0, 0.3272] | [0.0, 0.3358] | [0.0151, 0.8967] | [0.0, 0.4994] | [0.0034, 0.3973] |
| (18/44) | Est. Bias | 0.0000 | 0.0002 | -0.0003 | -0.0001 | -0.0001 | 0.0000 |
| | BCa | *(0.1410, 0.2613)* | *(0.0263, 0.1206)* | *(0.0965, 0.1906)* | *(0.1797, 0.2843)* | *(0.0741, 0.1522)* | *(0.0857, 0.1499)* |
| Northern | Mean | 0.2355 | 0.0582 | 0.1773 | 0.2781 | 0.11890 | 0.1592 |
| 2000/01 | Min/Max | [0.0, 0.4066] | [0.0, 0.2289] | [0.0, 0.3308] | [0.0035, 0.5202] | [0.0, 0.4028] | [0.0035, 0.4539] |
| (24/50) | Est. Bias | 0.0000 | 0.0000 | -0.0000 | -0.0002 | -0.0006 | 0.0000 |
| | BCa | *(0.1884, 0.2772)* | *(0.0344, 0.0899)* | *(0.1393, 0.2144)* | *(0.2438, 0.3096)* | *(0.0879, 0.159)* | *(0.1313, 0.1905)* |
| Northern | Mean | 0.3598 | 0.2023 | 0.16250 | 0.4581 | 0.2366 | 0.2215 |
| 2004/05 | Min/Max | [0.0, 0.5554] | [0.0, 0.4728] | [0.0, 0.54670] | [0.0, 0.7478] | [0.0, 0.7092] | [0.0, 0.6515] |
| (22/104) | Est. Bias | 0.0004 | 0.0006 | 0.0003 | 0.0000 | 0.0002 | 0.0000 |
| | BCa | *(0.2905, 0.4147)* | *(0.1324, 0.2662)* | *(0.1042, 0.2435)* | *(0.4264, 0.4878)* | *(0.2034, 0.2710)* | *(0.1957, 0.2527)* |
| Northern | Mean | 0.2840 | 0.0591 | 0.2280 | 0.3319 | 0.14990 | 0.18200 |
| 2007/08 | Min/Max | [0.0, 0.7170] | [0.0, 0.5277] | [0.0, 0.5072] | [0.0, 0.7968] | [0.0, 0.7550] | [0.0, 0.6167] |
| (19/74) | Est. Bias | -0.0007 | -0.0001 | 0.0002 | 0.0005 | 0.0002 | -0.0001 |
| | BCa | *(0.2240, 0.3691)* | *(0.0214, 0.1616)* | *(0.1783, 0.2836)* | *(0.2947, 0.3753)* | *(0.1193, 0.1913)* | *(0.1543, 0.2169)* |
| Southern | Mean | 0.1979 | 0.0447 | 0.1531 | 22130 | 0.1073 | 0.1140 |
| 1997/98 | Min/Max | [0.0, 0.8967] | [0.0, 0.2590] | [0.0, 0.3109] | [0.0151, 0.8967] | [0.0, 0.4994] | [0.0034, 0.3973] |
| (26/44) | Est. Bias | 0.0008 | 0.0001 | 0.0002 | -0.0001 | -0.0001 | 0.0000 |
| | BCa | *(0.1426, 0.3014)* | *(0.0234, 0.0784)* | *(0.1062, 0.2592)* | *(0.1797, 0.2843)* | *(0.0741, 0.1522)* | *(0.0857, 0.1499)* |
| Southern | Mean | 0.2600 | 0.0731 | 0.1870 | 0.2781 | 0.11890 | 0.1592 |
| 2000/01 | Min/Max | [0.0, 0.4350] | [0.0, 0.3311] | [0.0, 0.4350] | [0.0035, 0.5202] | [0.0, 0.4028] | [0.0035, 0.4539] |
| (26/50) | Est. Bias | -0.0000 | -0.0002 | -0.0000 | -0.0002 | -0.0006 | 0.0000 |
| | BCa | *(0.2135, 0.2983)* | *(0.0423, 0.1163)* | *(0.1498, 0.2268)* | *(0.2438, 0.3096)* | *(0.0879, 0.159)* | *(0.1313, 0.1905)* |
| Southern | Mean | 0.3357 | 0.1585 | 0.1778 | 0.4581 | 0.2366 | 0.2215 |
| 2004/05 | Min/Max | [0.0, 0.5786] | [0.0, 0.5106] | [0.0, 0.3915] | [0.0, 0.7478] | [0.0, 0.7092] | [0.0, 0.6515] |
| (82/104) | Est. Bias | 0.0000 | 0.0003 | -0.0000 | 0.0000 | 0.0002 | 0.0000 |
| | BCa | *(0.3062, 0.3630)* | *(0.1333, 0.1846)* | *(0.1562, 0.1994)* | *(0.4264, 0.4878)* | *(0.2034, 0.2710)* | *(0.1957, 0.2527)* |
| Southern | Mean | 0.3016 | 0.1149 | 0.1867 | 0.3319 | 0.14990 | 0.18200 |
| 2007/08 | Min/Max | [0.0, 0.7048] | [0.0, 0.5843] | [0.0, 0.5494] | [0.0, 0.7968] | [0.0, 0.7550] | [0.0, 0.6167] |
| (55/74) | Est. Bias | -0.0006 | -0.0002 | 0.0000 | 0.0005 | 0.0002 | -0.0001 |
| | BCa | *(0.2634, 0.3470)* | *(0.0864, 0.1539)* | *(0.1565, 0.2241)* | *(0.2947, 0.3753)* | *(0.1193, 0.1913)* | *(0.1543, 0.2169)* |

*NB: The values are inefficiency measures. For example, 0.2005 means 20.05% inefficiency (i.e., 80% efficiency). Notice that in the overall meta-frontier estimates column we report same results for both the Northern and Southern Zones. This is so because as illustrated in Figure 5, these represent the same meta-frontier against which the two zones are evaluated. In Section 5, we indicated that the meta-frontier is a frontier constructed by pooling all firms from all groups, meaning the estimates are for all firms in all groups.*

Let us first consider profit efficiency estimates calculated using only the observations from a single zone and period (left-hand column of Table 3). These compare inefficiencies only related to the closest peers in time and space. Note that the Nerlovian profit efficiency is broken down into technical and allocative inefficiency components in the subsequent columns.

First, we analyze the period zonal frontier estimates of the Northern Zone (first three columns of the upper part of Table 3). In this zone the mean profit inefficiency (efficiency) is lowest (highest), at about 20% (80%), in the 1997/98 fishing period, increasing (decreasing) to the lowest of nearly 36% (64%) in the 2004/05 period. Thereafter, mean profit inefficiency (efficiency) fell (rose) to about 28% (72%) in the 2007/08 fishing period. A close look at the bias accelerated corrected intervals (BCas) shows that the 2007/08 mean is quite close to that of 1997/98. The period mean measures show that profit inefficiency (efficiency) in the Northern Zone can be largely attributed to allocative inefficiency (efficiency), with the exception of the 2004/05 period where technical inefficiency (efficiency) is highest (lowest) at 20% (80%). In all other periods technical inefficiency (efficiency) registers a mean value of 6% (94%), on average. The estimated bias, in all cases, shows that the mean estimates are not significantly corrected upwards or downwards. The relatively higher maximum values in 2004/05 and 2007/08 periods, show that there are greater variations in the distribution of inefficiency measures in these periods compared to other periods.

Next, the Southern Zone period estimates are considered (first three columns of the lower part of Table 3). In the Southern Zone the mean profit inefficiency rose from about 20% in 1997/98 fishing period to nearly 34% in the 2004/05 period, falling slightly to approximately 30% in 2007/08. Technical inefficiency also rose from 4% in 1997/98 to the highest of about 16% in 2004/05, falling to nearly 11% in 2007/08. In all cases the allocative inefficiency, which rose from 15% in 1997/98 to about 19% in 2007/08, with just about 1 percentage point drop in 2004/05, explains the profit inefficiencies. It is interesting to note that though the mean profit inefficiency (efficiency) in the 2004/05 period is highest (lowest), the variability in the estimates is not as high as observed in the 1997/98 and 2007/08 periods where inefficiencies

(efficiencies) are relatively lower (higher).

In the next two paragraphs we compare the period zonal estimates with corresponding overall period meta-frontier estimates. In the right-hand three columns of Table 3, are the estimates of overall period meta-frontier estimates computed by pooling firms from both zones for each period. That is, using all Northern and Southern Zone observations in each period as peers. Graphically, this would be the meta-frontier picture illustrated in Figure 5. We start by looking at the Northern Zone period estimates. The period inefficiency estimates for the Northern Zone are lower than the corresponding period overall meta-frontier estimates. This is expected because firms compared to a small local group of peers may appear to be doing well, but may perform badly when compared with peers from other regions (zones, in this case). The profit inefficiency (efficiency) in the periods appear to be close to the corresponding overall meta-frontier estimates, in absolute terms.

The technical inefficiencies, on the other hand, show significant absolute differences. This is also expected for two reasons. The first is attributed to the fact mentioned earlier; firms in their own group may perform better than when grouped with peers from other groups, that is, when compared with peers in the meta-frontier group. Secondly, the higher number of observations used in the computation of the meta-frontier measures play significant role in correcting for the dimensionality problem and, therefore, reducing biases reflected by small numbers. For example, in the case of the 1997/98 period, the period measures for the zone are obtained using 18 observations, whereas the meta-frontier used 44 observations, that is, 18 from the Northern Zone and 26 from the Southern Zone. Observe that the relatively low technical inefficiency estimates under period zonal frontiers in this case means that profit inefficiency would be largely explained by allocative inefficiencies. Under meta-frontier, however, the picture is not straight forward. Profit inefficiencies in the Northern Zone for 1997/98, under meta-frontier, appear to be equally explained by technical and allocative inefficiencies, whereas in the 2000/01 and 2007/08 periods profit inefficiencies under meta-frontier are clearly explained by allocative inefficiencies. Profit inefficiency in 2004/05, on the other hand, can be clearly attributed to technical inefficiency. This means that increases in observations under meta-frontier makes it difficult to identify a single source of profit inefficiency for all periods in the zone.

Next, we consider the Southern Zone. In the Southern Zone, as observed in the case of the Northern Zone, the period inefficiency measures are lower than the corresponding meta-frontier measures. Again, unlike the profit inefficiency measures, the technical inefficiencies are much lower for the zonal period estimates than the corresponding meta-frontier estimates. These are expected, and explained by similar reasons given in the Northern case. It is noted, however, that whereas period profit inefficiencies in this zone are clearly explained by allocative inefficiencies for all periods, the meta-frontier profit inefficiency are not the same for different periods. Consequences of the influence of large numbers on technical inefficiency measures and the effect on profit inefficiency under the meta-frontier are discussed in the previous paragraph. It is also observed that the Southern Zone generally accounts for the variations in the profit inefficiency distributions of the meta-frontier, particularly as observed in the minimum and maximum values in the 1997/98 period.

We now explain the possible causes of the inefficiency measures observed in both fisheries. Changes in efficiency levels observed in Table 3, particularly with regards to increase in allocative inefficiency in the Northern Zone, could be attributed to a number of issues identified in the SARDI (2009) report. Between 1998 and 2008 harvest in the Northern Zone declined by nearly 60% with less than proportionate reduction in effort for the same period. Over this period catch per unit of effort (CUE) fell by about 52%, that is, from 1.40kg/pot lift to 0.67kg/pot lift. Such declines are observed across the MFAs in the zone (SARDI, 2010). The picture is no different when we extend the analysis one period back. The fall in harvest between 1997 and 2008 was about 57% with effort falling only by about 17% (i.e., 16.67%) over the same period. Persistent downward movement in CUE is reported over the period 1999 to 2008 (SARDI, 2009). CUE (also refered to as: catch rate) in the zone increased from 1.40kg/pot lift in 1997 to the highest of nearly 1.44kg/pot lift in 1999, falling thereafter to a low of about 0.67kg/pot lift in 2008. The disproportionate declines in effort compared to falls in catch leading to persistent and sharp declines in CUE help explain cost increases, falls (increases) in profit and allocative efficiencies (inefficiencies) over the period under investigation. Fluctuations in biomass, and harvest values in the rock lobster fishery, shown in Figure 1, together with falls in boat equity profits (see Figure 3) in the period under review further confirm our results.

As in the case of the Northern Zone, our results compare reasonably well with the underlying fundamental changes in in the Southern Zone over the period under investigation. Whereas catch rates declined over the period, effort increased at the same time. The Southern Zone fishery performed best in 2002 in terms of catch rate. After a period of increases in catch rate, from about 0.98kg/pot lift in 1998 to a high of about 2.07kg/pot lift in 2002, the catch rate fell persistently. The fall in CUE reached a low of 1.6kg/pot lift in 2004 (PIRSA, 2007). This trend is observed across all regions (MFAs) in the zone. Effort, on the other hand, increased in the Southern Zone by about 96% between 2003 and 2008 (SARDI, 2009). Other factors such as declines in biomass levels, harvest value, and equity profit levels over the period, as mentioned earlier, help explain the declines in efficiency levels in this zone. Next, we provide comparative analysis of the two fisheries, using their period meta-frontier inefficiency estimates.

In Table 4 we compare the inefficiency scores of the Northern and Southern Zones under meta-frontier. From Table 4 it is observed that on average the Northern Zone fishery appears to perform a little better than its Southern Zone counterpart, in absolute terms, across all periods except in 2000/01 fishing period. In general the results appear quite close in absolute terms. To test for equality of mean estimates between the two zones, we use the Welch two sample t-test.

Table 4: Inefficiency Estimates (Periods and Period meta-frontiers): Northern and Southern Zones

| | | Northern Zone (Period meta-frontier) | | | Southern Zone (Period meta-frontier) | | |
|---|---|---|---|---|---|---|---|
| Period | Statistical Measure | Nerlovian Profit Eff. | Technical Eff. | Allocative Eff. | Nerlovian Profit Eff. | Technical Eff. | Allocative Eff. |
| 1997/98 | Mean | 0.2152 | 0.10670 | 0.1085 | 0.2255 | 0.1078 | 0.1177 |
| | Min/Max | [0.0151, 0.4529] | [0.0, 0.4216] | [0.0071, 0.3569] | [0.0231, 0.8967] | [0.0, 0.4994] | [0.0034, 0.3973] |
| | Est. Bias | 0.0000 | 0.0002 | 0.0000 | -0.0000 | 0.0005 | 0.00017 |
| | BCa | *(0.1534, 0.2822)* | *(0.0548, 0.1834)* | *(0.0685, 0.1647)* | *(0.1692, 0.3231)* | *(0.0683, 0.1666)* | *(0.0824, 0.1696)* |
| | No. of Obs | | 18 | | | 26 | |
| 2000/01 | Mean | 0.2791 | 0.1409 | 0.1382 | 0.2771 | 0.0985 | 0.1786 |
| | Min/Max | [0.0329, 0.4504] | [0.0, 0.4028] | [0.0051, 0.3723] | [0.0035, 0.5202] | [0.0, 0.3750] | [0.0035, 0.4539] |
| | Est. Bias | -0.0002 | 0.0000 | 0.0000 | 0.0007 | -0.0000 | -0.0002 |
| | BCa | *(0.2266, 0.3218)* | *(0.0910, 0.1987)* | *(0.1015, 0.1895)* | *(0.2277, 0.3204)* | *(0.0595, 0.1540)* | *(0.1407, 0.2241)* |
| | No. of Obs. | | 24 | | | 26 | |
| 2004/05 | Mean | 0.4088 | 0.2229 | 0.1859 | 0.4713 | 0.2403 | 0.2310 |
| | Min/Max | [0.0, 0.6387] | [0.0, 0.4943] | [0.0, 0.5849] | [0.0909, 0.7478] | [0.0, 0.7092] | [0.0074, 0.6515] |
| | Est. Bias | -0.0008 | 0.0005 | -0.0009 | -0.0000 | -0.0003 | 0.0002 |
| | BCa | *(0.3282, 0.4724)* | *(0.1590, 0.2879)* | *(0.1367, 0.2694)* | *(0.4375, 0.5039)* | *(0.2022, 0.2792)* | *(0.2018, 0.2640)* |
| | No. of Obs. | | 22 | | | 82 | |
| 2007/08 | Mean | 0.2985 | 0.1253 | 0.1732 | 0.3435 | 0.1584 | 0.1850 |
| | Min/Max | [0.0099, 0.7330] | [0.0, 0.4069] | [0.0099, 0.5628] | [0.0, 0.7968] | [0.0, 0.7550] | [0.0, 0.6167] |
| | Est. Bias | -0.0006 | 0.0005 | 0.0004 | 0.0004 | 0.0005 | -0.0005 |
| | BCa | *(0.2418, 0.3810)* | *(0.0827, 0.1799)* | *(0.1238, 0.2472)* | *(0.2996, 0.3966)* | *(0.1207, 0.2068)* | *(0.1525, 0.2257)* |
| | No. of Obs. | | 19 | | | 55 | |

*NB: The values are inefficiency measures. For example, 0.2005 means 20.05% inefficiency (i.e., 80% efficiency)*

We do not find enough evidence to reject the alternate hypothesis that the meta-frontier mean inefficiency estimates in the two zones are indeed different. Table 5 in Appendix B shows results of the t-tests. We note, however, that mean technical inefficiency (efficiency) over the period, 1997 – 2008, on average, are the same at 15% (85%).

To get a more general picture of the distribution of the inefficiency estimates in the two fisheries, Figure 6 presents kernel density distribution of the period-by-period meta-frontier (overall) estimates. To avoid imposing any restrictions on the estimates we use a non-parametric kernel density method, the Epanechnikov method,[24] with

[24] In practice the Epanechnikov and Gaussian methods are often used. The literature points out that the choice of either of these has little impact on the results. The bandwidths are different for the different efficiency measures since their distributions are different. We also note that ideally the density graphs should have the same scale for the horizontal axis. However, doing this overly

different bandwidths for each distribution of the bootstrapped efficiency estimates. Recall that the efficiency estimates were replicated using non-parametric bootstrap method with 5000 replications for each. By avoiding imposing restrictions on the estimates we allow the estimates to speak for themselves.

minimizes some of the graphs whose distributions are in smaller intervals. Recall that the efficiency scores for NE, DDF and AE, fall in different intervals. Minimizing some of the graphs would not create the pictorial impression they are meant to have. It is therefore important that the kernel density distributions between zones are viewed within periods and not across periods, to avoid any confusion.

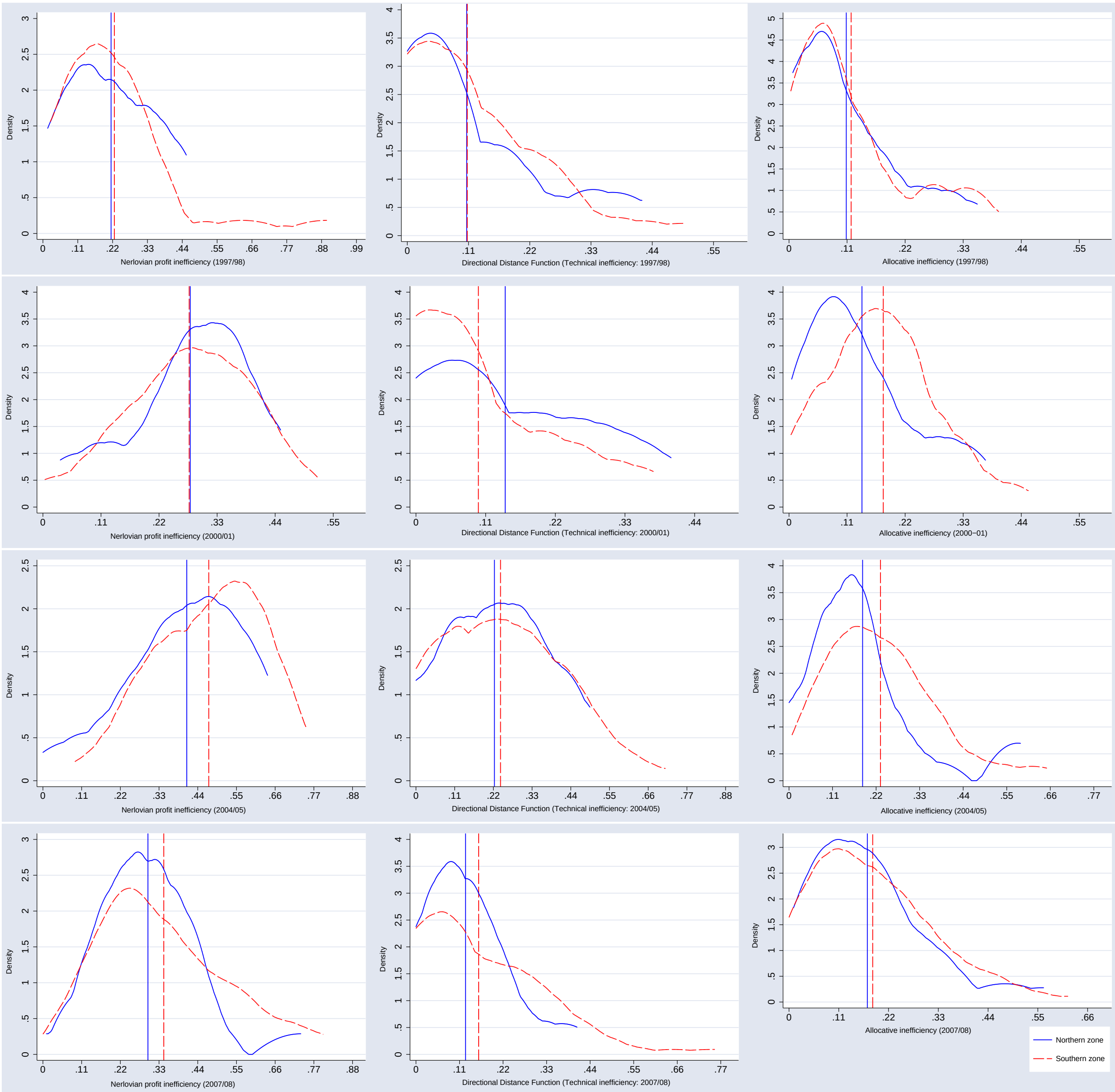


Figure 6: Distribution of bias-corrected period-by-period meta-frontier (overall) estimates.

These density plots show the percentage of times that a particular inefficiency score is computed. For example, the top left diagram shows that an inefficiency score of approximately 0.22 (22%) was computed nearly 2.5% of the time for the Southern Zone fishery. It can be observed that apart from the 2000/01 and 2004/05 periods profit inefficiency estimates are positively skewed to the right. This shows a pull of the mean estimates (the straight lines) more to the right of their modes. In addition skewness in the Southern Zone distributions is more pronounced than in the Northern Zone. The greater skewness in the Southern fishery offers another possible explanation to its relatively higher mean inefficiency levels. In the 1997/98 distributions the two fisheries show more concentration in the lower inefficiency (higher efficiency) regions, with the Northern fishery mean inefficiencies being generally lower than those of the Southern fishery. A closer look at the Figure shows that in this period the two fisheries' estimates present mulch-modal distributions for profit, technical, and allocative inefficiencies.

The kernel density is essentially a smooth version of histogram. This means that small bumps in Figure 6 actually depict multiple modes in the distribution. Though the modal bumps in the Southern fishery are not as pronounced as observed in the Northern fishery, there is a clear indication that there are a number of groupings of inefficiency estimates in both fisheries. With the exception of the 2000/01 and 2004/05 periods, the picture in other periods is not much different from that of 1997/98. In the 2000/01 and 2004/05 periods the profit inefficiencies for both fisheries are more concentrated around the 27-33% and 46-57% estimates for the two periods, respectively. This is higher than what is observed in all other periods.

It was earlier noted that vessels in the Northern Zone fish for between one to ten days per trip, while their southern counterparts generally undertake day trips, fishing close to their home ports. One would, therefore, expect that firms in the Southern Zone would be more profit and allocatively efficient, given their lower operational costs. However, a possible outcome of such fishing strategy could be that vessels in the Southern Zone will make more trips, on average, than those in the Northern Zone. This means that though fishing cost in the Northern Zone may be higher than in the Southern Zone due to longer travel distance, the Northern Zone may be more allocatively efficient because on average they make less frequent trips. Further to that, a trend observed since the introduction of the quota system in the Northern Zone is that license holders fish in reduced area using the least fuel and time possible (PIRSA, 2007). Such operational strategies are likely to positively impact efficiency, particularly profit and allocative efficiency in the fishery.

Variations in economic performance is also attributed to market performance for particular lobster types within regions in the Northern Zone (PIRSA, 2007, pp. 47-48). We further observe that whereas effort decreased in the Northern Zone between 1997 and 2007, between 2003 and 2008 effort increased in the Southern Zone by about 96%. At the same time, however, catch rate in the Southern Zone declined considerably between 2003 and 2009, as earlier mentioned. This could possibly be another underlying factor explaining the poorer efficiency performance in the Southern Zone relative to the Northern Zone. Further to that, results here are indication that even though the Southern Zone faces lower costs and earn relatively higher profits, given its technology firms in this zone are not making high enough profits to be comparatively more profit efficient.

One evidence is however clear, that the effects of poor performance in biomass levels, harvest level and CUE levels, exchange rate shocks with international trading partners, affected both zones significantly. This is particularly evident from the 2004/05 period efficiency performance. All efficiency measures for both zones in this period were lower, compared to other periods. Differences in the mean and maximum scores also show that there is greater variation among firms in the Southern Zone compared to those in the Northern Zone.

# 7 Conclusion

In the past efficiency investigations in fisheries have generally focused on productivity, technical efficiency, cost, and in some instances, revenue efficiency. Attention to profit efficiency analysis has been a more recent development. This paper has argued that the profit efficiency concept is superior to that of cost when evaluating overall performance of firms. Profit efficiency evaluation is an important exercise that helps to identify inefficiencies resulting from choosing suboptimal input-output mix. For these and other reasons emphasized in this paper, the importance of theoretical and empirical analysis of profit efficiency measures can not be ignored. The paper emphasized that the South Australian Rock Lobster Fishery is an important sector of the state's fishing industry, making significant contributions to the state's economy. This makes the critical examination of the fishery's economic performance crucial to evaluating the sustainability of the fishery.

This paper applied a new method of profit efficiency analysis to the South Australian Rock Lobster Fishery. In particular we used a combination of the Nerlovian and Directional Distance Function methods to decompose profit efficiency into its technical and allocative components. To our knowledge there are no studies that have applied these methods to investigate profit efficiency in this fishery. Previous analysis of the two fisheries, based on cost and revenues, indicate that the Southern Zone fishery is more profitable than the Northern Zone and, therefore perceived to be more profit efficient. We tested if indeed the Southern Zone fishery is more profit efficient compared to its Northern counterpart. In contrast to the perception about profit performance in the fishery we find that the Northern Zone fishery appears to have higher profit efficiency than the Southern Zone, for the period investigated. Specifically, we showed that though operational cost in the Southern Zone is lower than is observed in the Northern Zone, on average the Northern Zone is more profit efficient than the Southern Zone.

Results in this paper also show that in both the Northern and Southern Zones profit efficiency can be largely attributed to allocative inefficiency, except for the 2004/05 period when technical inefficiency contributed more to profit inefficiency than did allocative inefficiency. The relatively high technical inefficiency levels in the 2004/05 period can be attributed to a number of challenges. Such challenges included significant drops in the biomass level, decline in harvest values due to exchange rate shocks, increases in effort coupled with significant drops in catch rate. These offer possible explanations to the poor economic performance in the fisheries investigated and will be examined in detail in the following paper.

Differences in mean and maximum efficiency measures suggest that there is greater variability in economic performance in the Southern Zone than observed in the Northern Zone. On a period by period basis, the Northern Zone appear to perform better than its southern counterpart in terms of profit efficiency. These differences do not appear significant in absolute terms. However, we do not find enough statistical evidence to reject the alternate hypothesis that mean efficiency performance are different in the two zones. The uniqueness of the bootstrapping method applied in the analysis was that it helped to obtain more reliable estimates and, draw reasonable statistical inferences from the results. Although the bootstrapping method was also applied to help address the sensitivity of our methods to small sample sizes, we caution that due to small numbers, particularly in the case of the Northern Zone, these results be treated with care.

This paper has argued that the Nerlovian method of efficiency evaluation possesses decomposition power, together with the ability to overcome the negative profits problem, computationally. The directional distance function approach has also been shown to posses advantage over the Shephard type distance functions. It was argued, for example, that the additive nature of the profit function makes the radial Shephard type distance functions less appropriate dual model technology for profit efficiency analysis. The directional distance function, on the other hand, has been shown to allow factors to change in opposite directions. In other words, it allows simultaneous output expansion and input contraction.

A number of methods, including parametric and non-parametric, have been employed to analyze profitability and other economic performance in the past. Despite the presence of these methods consensus on the appropriate technique, in the context of profit efficiency, is yet to be achieved. For example, parametric techniques such as stochastic frontier, have been found not to be flexible when it comes to profit decomposition. Further to that, while methods such as the INPD possess strong decomposition power, their ability to overcome the negative profits problem, particularly in fisheries, still remains a drawback. A unique advantage of the Nerlovian method in this regard is that it poses no computational problem when it comes to negative profits. We acknowledge, however, that in fisheries where negative profits are a problem, the Nerlovian method may not be solving the negative profits challenge entirely. We emphasize, however, that the ability to include negative profits in the initial computations is a huge advantage of the Nerlovian method, compared to others. Finally, to further illuminate the true potential of the methods employed in this paper in fisheries, future work will focus on applying the techniques in other fisheries.

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# Appendix

## A.1

Table 5: Results of Welch two sample t-test

| Period/Zone | Statistical Measure | Nerlovian Profit Eff. | Technical Eff. | Allocative Eff. |
|---|---|---|---|---|
| 1997 - 98 | | | | |
| Northern Zone | Mean | 0.2152 | 0.1067 | 0.1085 |
| Southern Zone | Mean | 0.2255 | 0.1078 | 0.1177 |
| | t | -0.2038 | -0.0252 | -0.2825 |
| | p-value | 0.8395 | 0.9800 | 0.7791 |
| | CI (95%) | *(-0.1121, 0.0916)* | *(-0.0852, 0.0831)* | *(-0.0754, 0.0569)* |
| 2000 - 01 | | | | |
| Northern Zone | Mean | 0.2791 | 0.1409 | 0.1382 |
| Southern Zone | Mean | 0.2771 | 0.0985 | 0.1786 |
| | t | 0.0572 | 1.1540 | -1.3205 |
| | p-value | 0.9546 | 0.2545 | 0.1930 |
| | CI (95%) | *(-0.0667, 0.0706)* | *(-0.0315, 0.1162)* | *(-0.1019, 0.0211)* |
| 2004 - 2005 | | | | |
| Northern Zone | Mean | 0.4088 | 0.2229 | 0.1859 |
| Southern Zone | Mean | 0.4713 | 0.2403 | 0.2310 |
| | t | -1.5400 | -0.4448 | -1.2408 |
| | p-value | 0.1338 | 0.6591 | 0.2240 |
| | CI (95%) | *(-0.1453, 0.0203)* | *(-0.0965, 0.0618)* | *(-0.1193, 0.0290)* |
| 2007 - 08 | | | | |
| Northern Zone | Mean | 0.2985 | 0.1253 | 0.1732 |
| Southern Zone | Mean | 0.3435 | 0.1584 | 0.1850 |
| | t | -1.0452 | -0.9788 | -0.3253 |
| | p-value | 0.3026 | 0.3328 | 0.7471 |
| | CI (95%) | *(-0.1322, 0.0422)* | *(-0.1014, 0.0350)* | *(-0.0859, 0.0623)* |

*NB: Values in parenthesis are the 95% confidence interval.*

**A.2**

Table 6: Average values of non-discretionary variables

| Period | Zone | Boat age | Boat length | Engine age | Electrical Equip. age |
|---|---|---|---|---|---|
| 1997/98 | NZ | 11.16 | 10.27 | 6.21 | 4.00 |
| | SZ | 12.82 | 11.94 | 7.02 | 4.54 |
| 2000/01 | NZ | 10.38 | 10.24 | 4.92 | 5.25 |
| | SZ | 13.89 | 11.89 | 4.28 | 5.22 |
| 2004/05 | NZ | 19.50 | 10.19 | 10.19 | 5.95 |
| | SZ | 14.17 | 11.77 | 5.73 | 6.00 |
| 2007/08 | NZ | 19.93 | 10.16 | 6.26 | 3.09 |
| | SZ | 12.58 | 11.83 | 6.73 | 4.04 |

*Notes: Boat age, Engine age and electrical equipment age are all in years. Boat length is in meters.*

**A.3**

Map of the Northern and Southern Zone Rock Lobster Fisheries, showing the respective Marine Fishing Areas (MFAs).

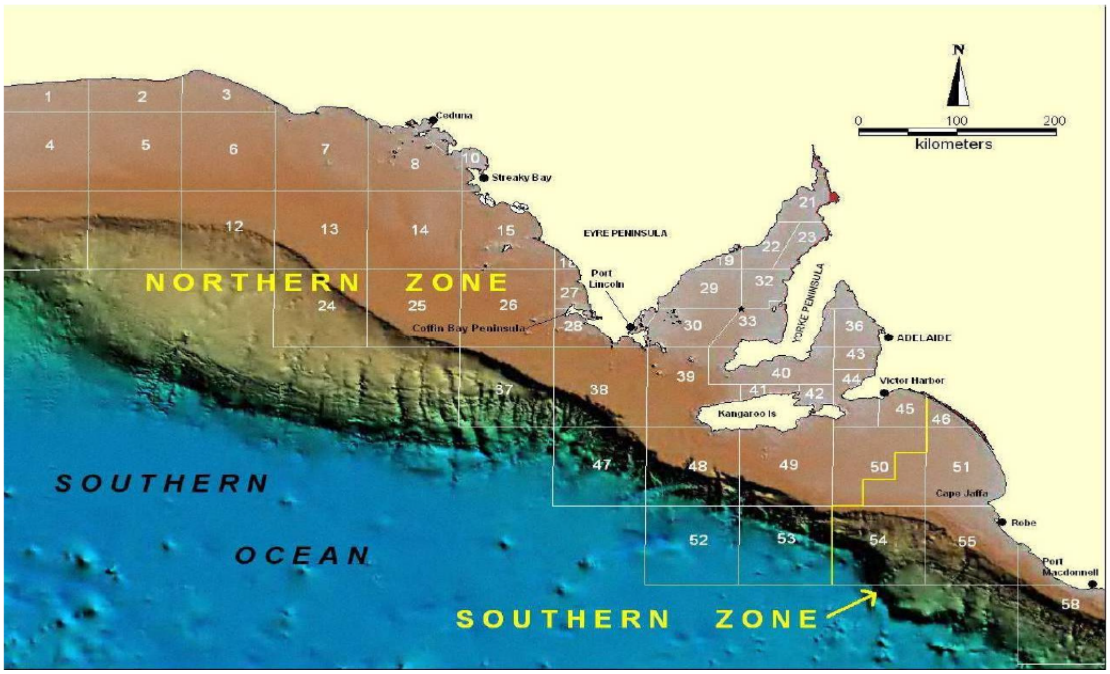


Figure 7: The Northern and Southern Zones and Marine Fishing Areas (MFAs) in the South Australia rock lobster fishery.

*Note: The numbered boxes are data collection map codes. (Source: SARDI publication, SARDI Research Report Series, No. 588, 2011)*